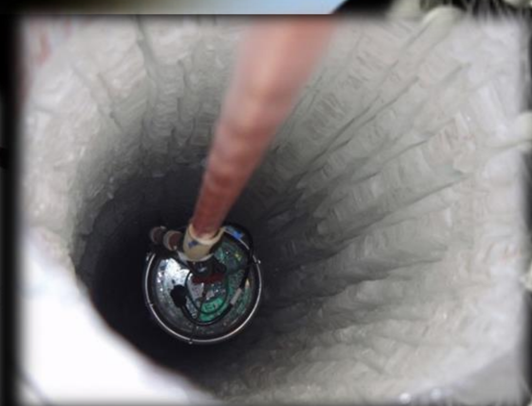
# Recent results from IceCube and the future high energy extension

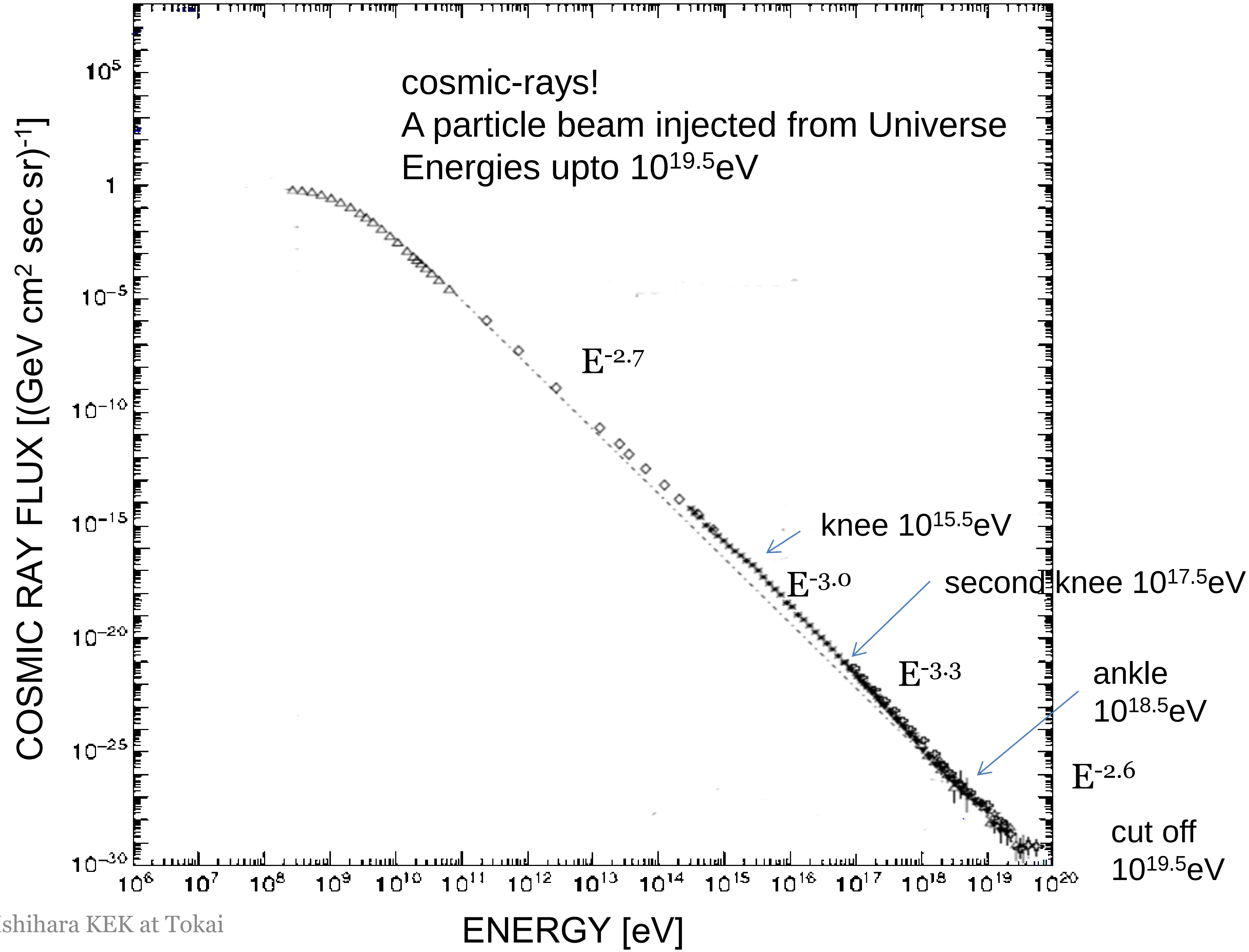
*Aya Ishihara*



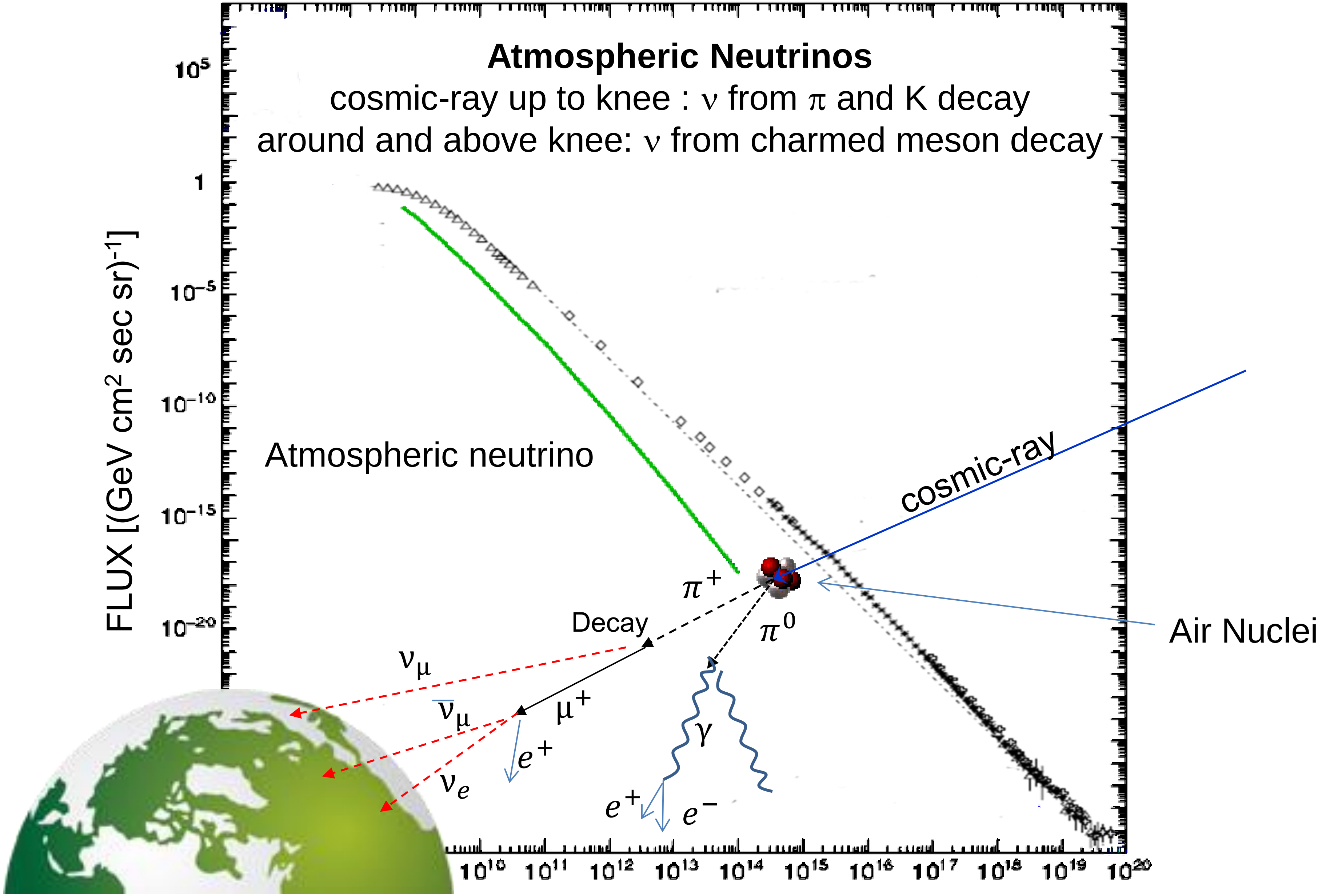
***KEK東海キャンパス***

***Feburary 20, 2015***

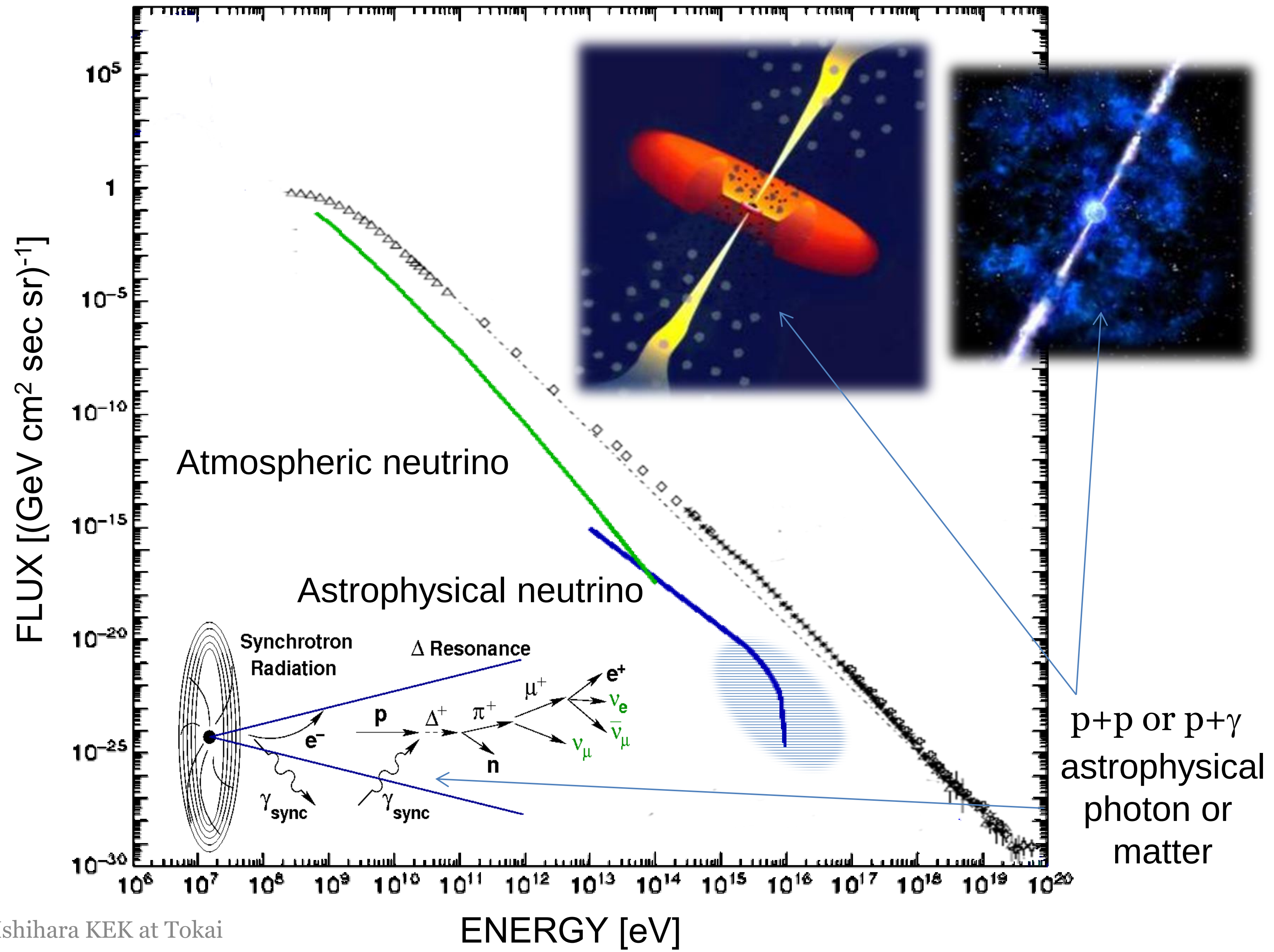
# Extremely-high energy emission in the Universe



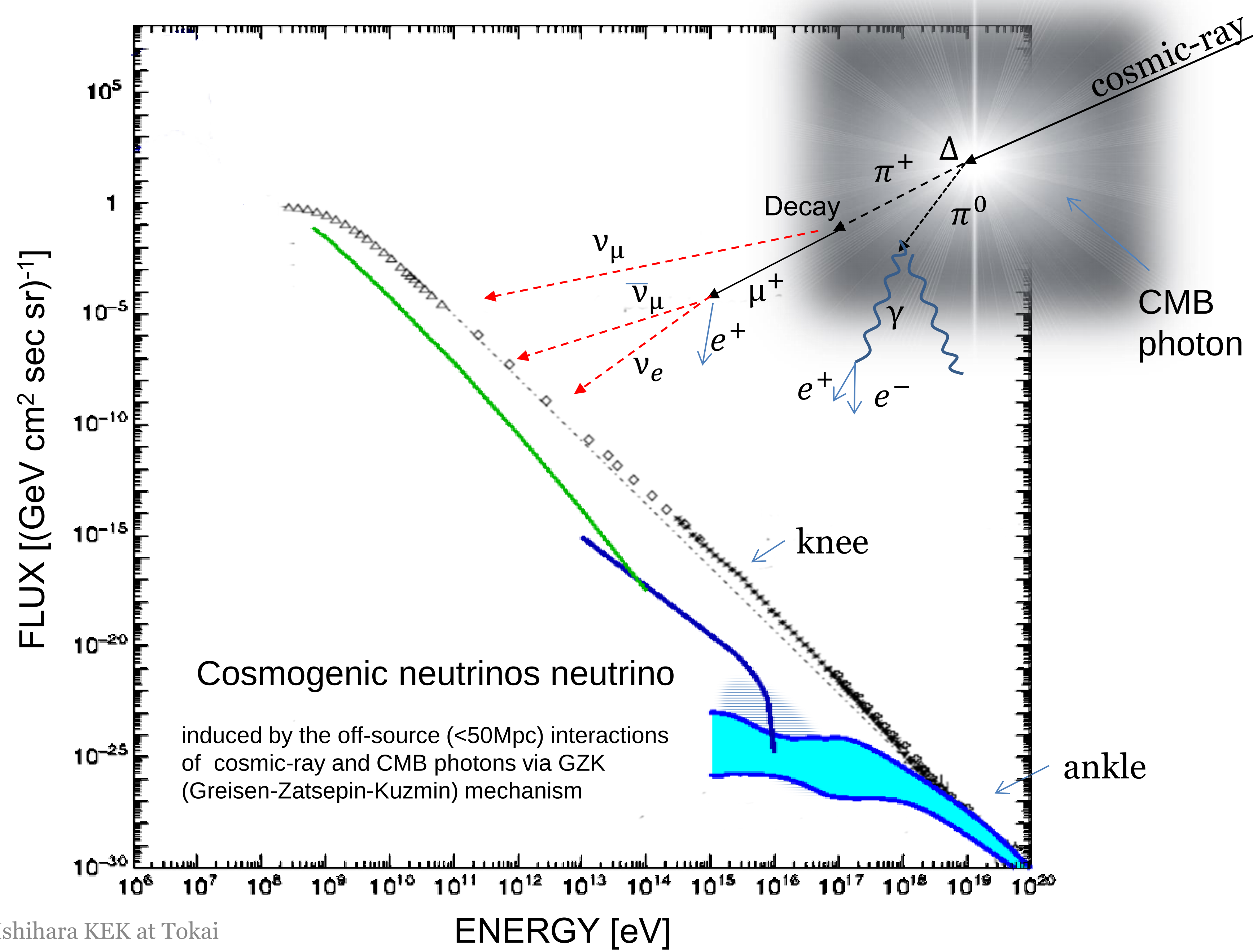
# High energy emission in the Universe



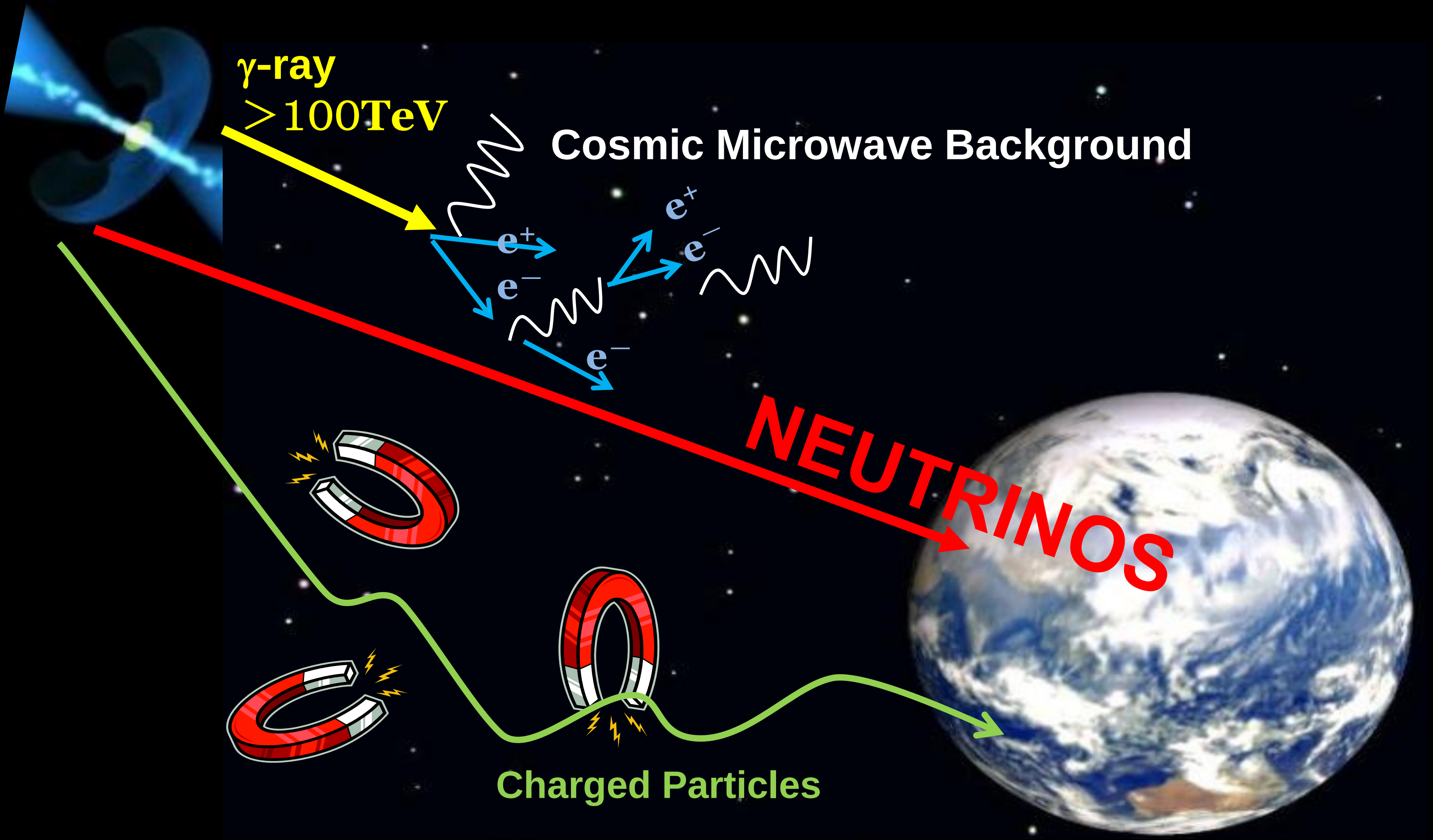
# Ultra-high energy neutrinos in the Universe



# Extremely-high energy neutrinos in the Universe

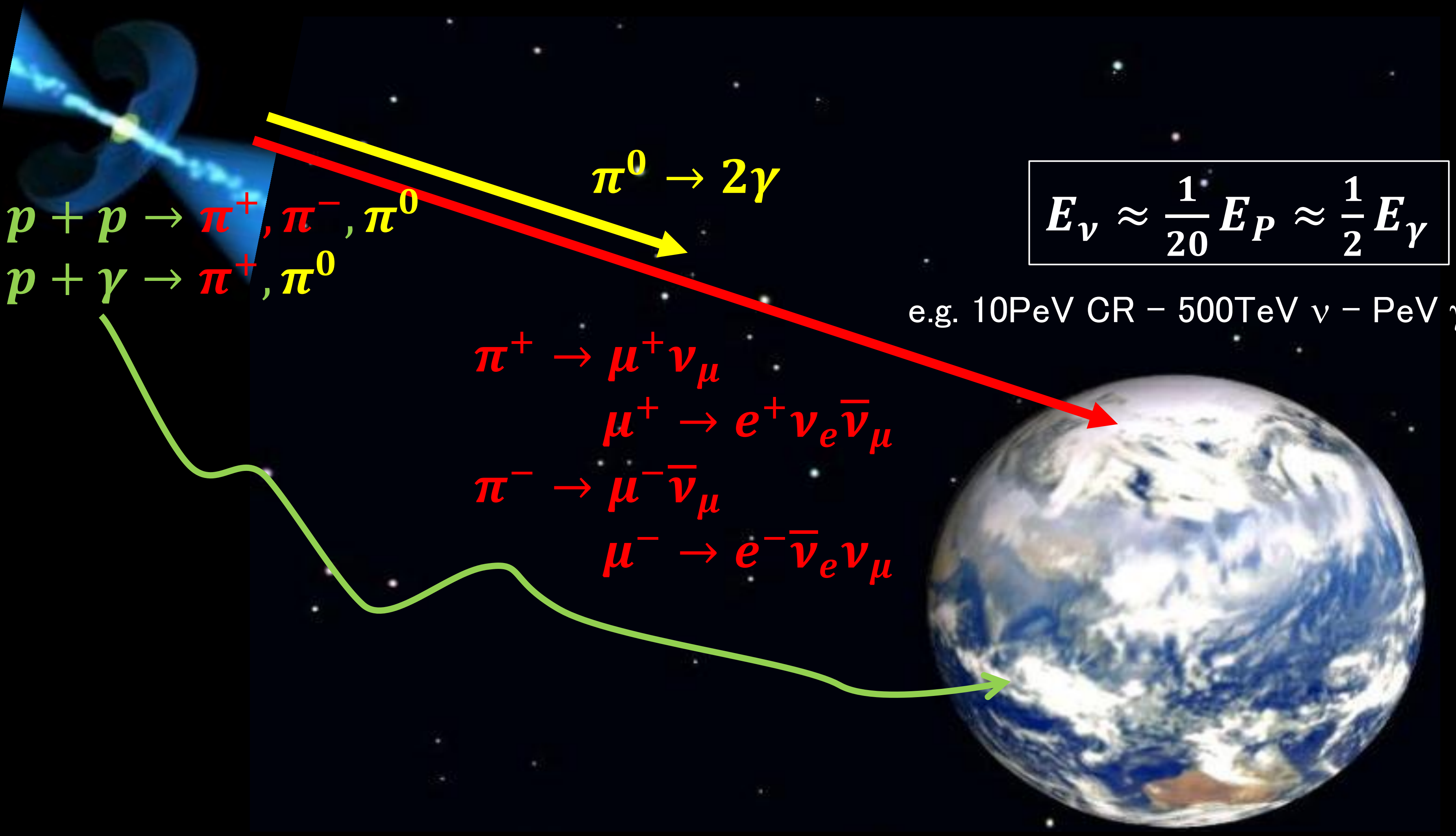


# Questions for the ultra-high energy neutrinos



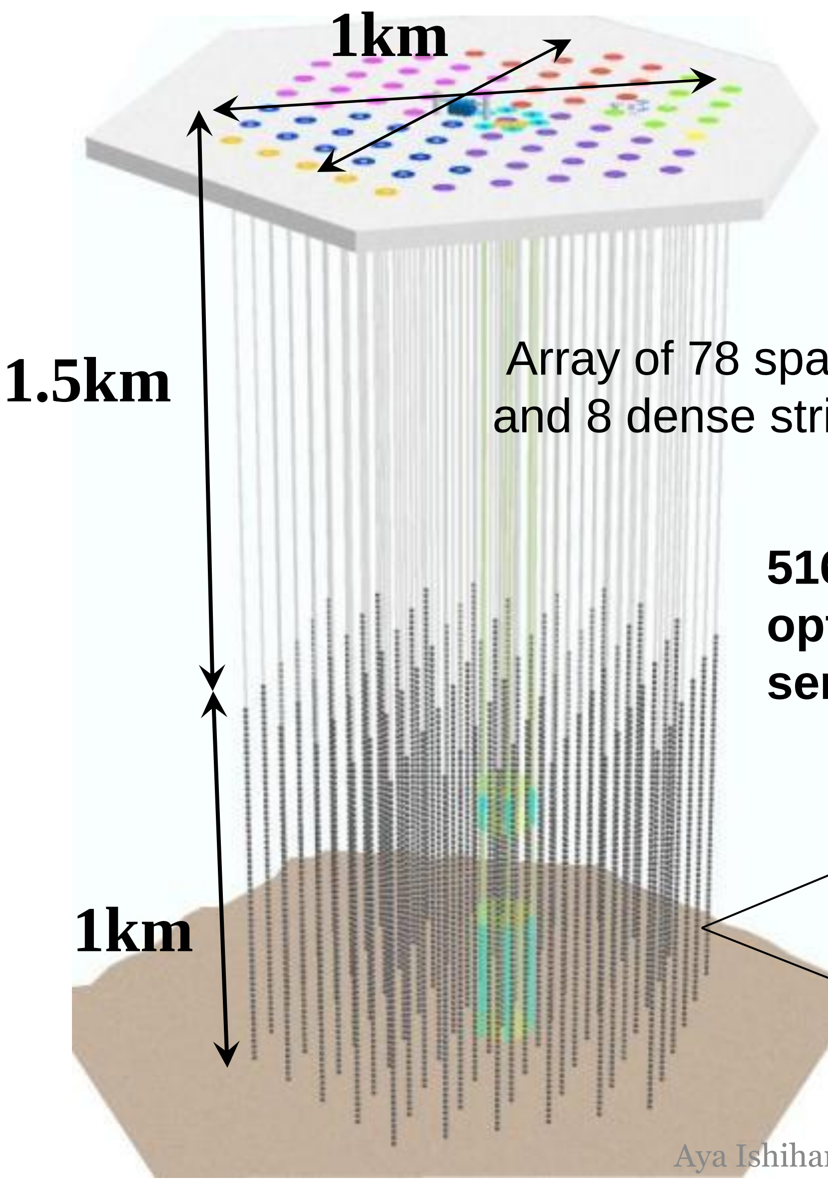
# Multi-Messenger detections and constraints

Still in the same origin, it is critical to observe them as multi-messengers!



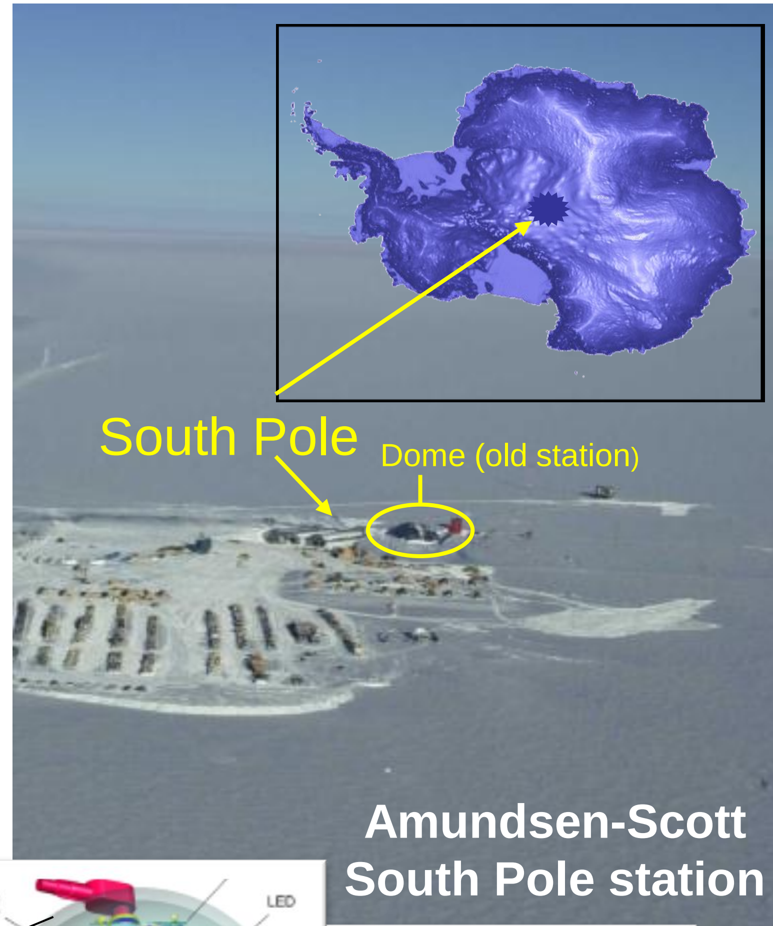
*The Largest Underground Detector in the world:*

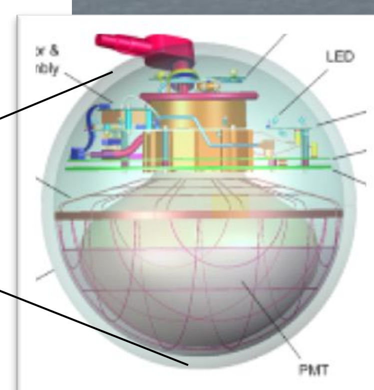
# The IceCube Detector



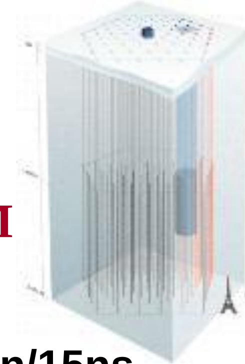

Array of 78 sparse and 8 dense strings

**5160 optical sensors**



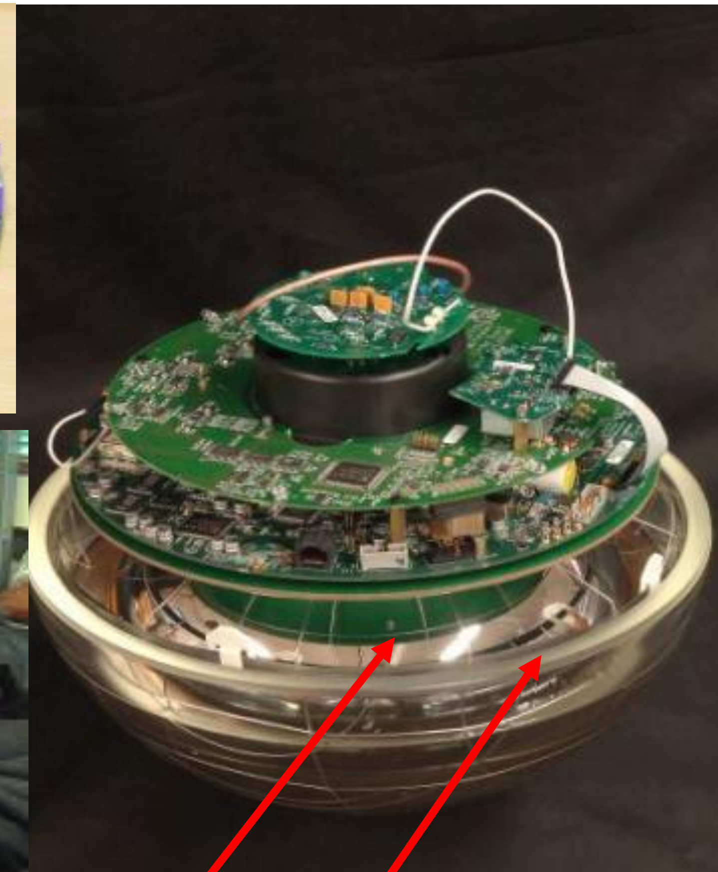

# Digital Optical Module



- **PMT: 10 inch Hamamatsu**
- **Power consumption: 3 W**
- **Digitize at 300 MHz for 400 ns with custom chip**
- **40 MHz for 6.4 μs with fast ADC**
- **Flasherboard with 12 LEDs**
- **Local HV**

**Waveforms, times digitized in each DOM**

- **Dynamic range 500 photoelectron/15ns**



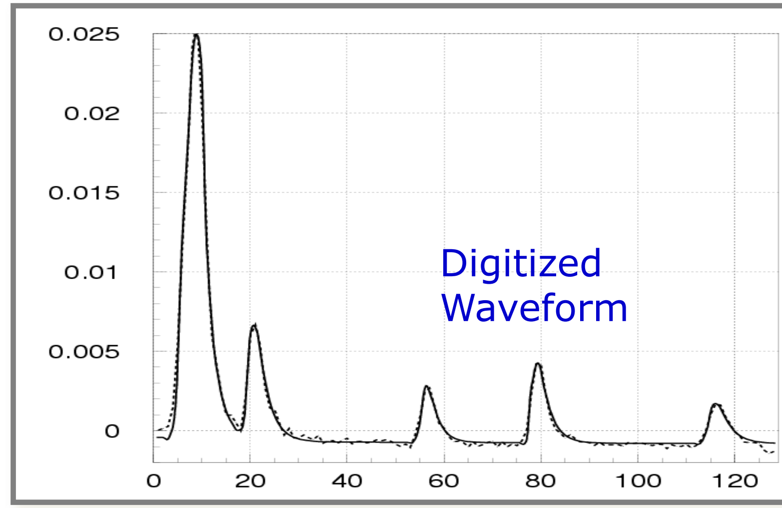
*Clock stability: $10^{-10} \approx 0.1$ nsec / sec*
*Synchronized to GPS time every $\approx$10 sec*
*Time calibration resolution = 2 nsec*

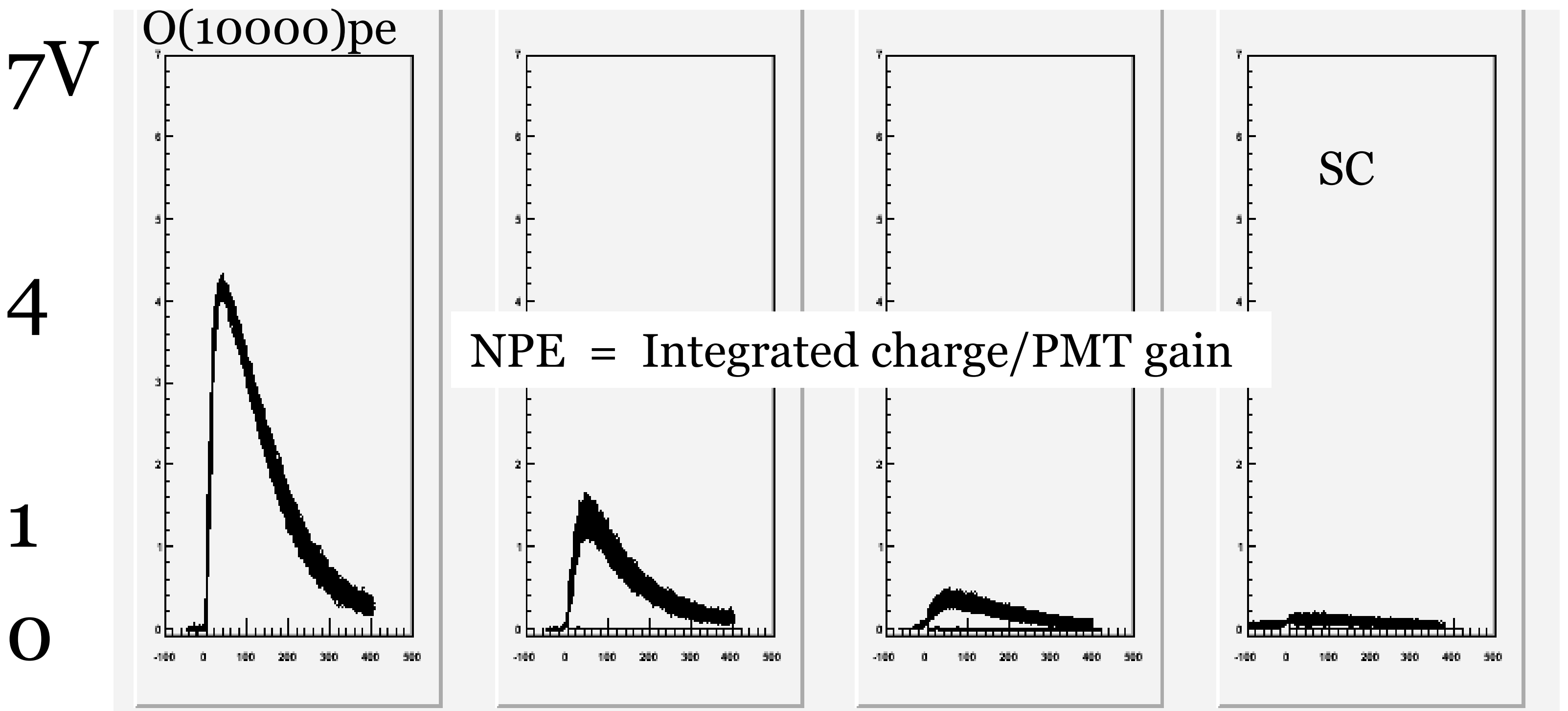
***25 cm PMT***
***33 cm Benthosphere***

# Waveform examples from spe to 10000 pe

*25 cm PMT*

single pe level

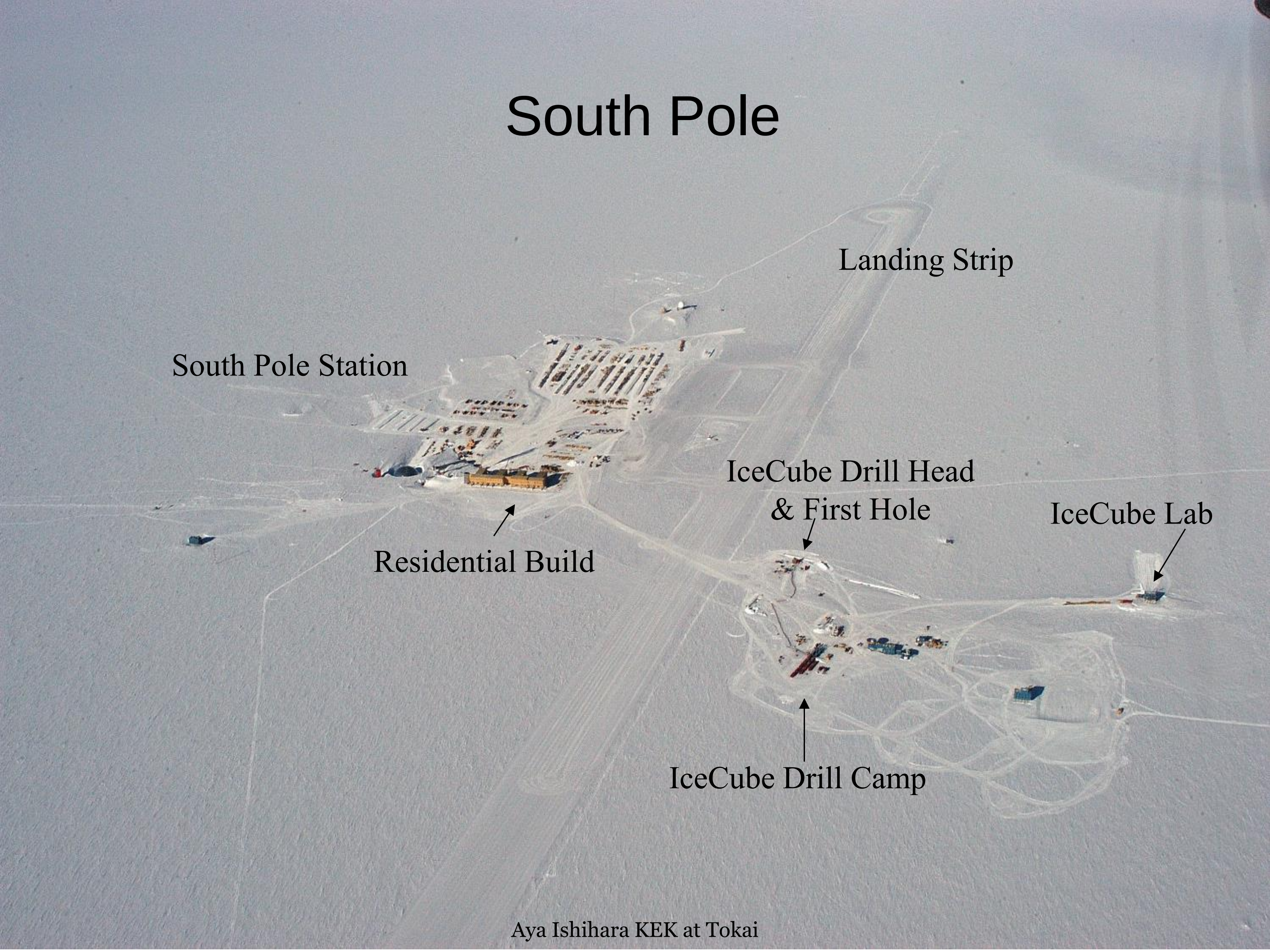



NPE = Integrated charge/PMT gain

Aya Ishihara

# South Pole


Landing Strip
South Pole Station
IceCube Drill Head
& First Hole
IceCube Lab
Residential Build
IceCube Drill Camp

# The IceCube LAB


60 photomultipliers/string
Aya Ishihara KEK at Tokai

# The IceCube Collaboration

http://icecube.wisc.edu


## International Funding Agencies

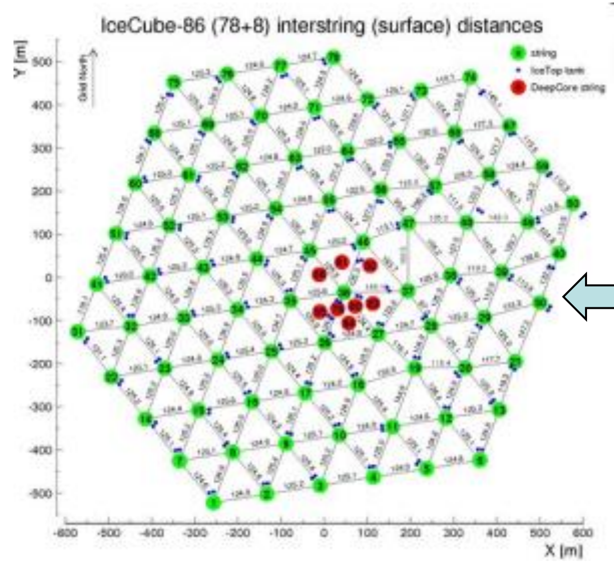
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)

Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)

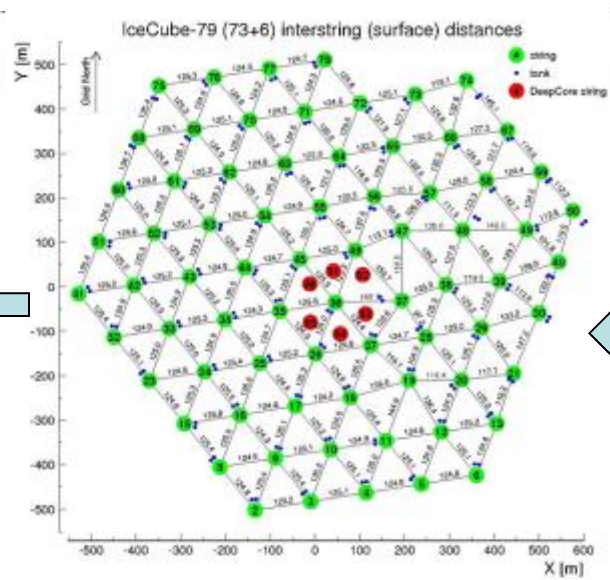
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

# The IceCube Construction and Runs

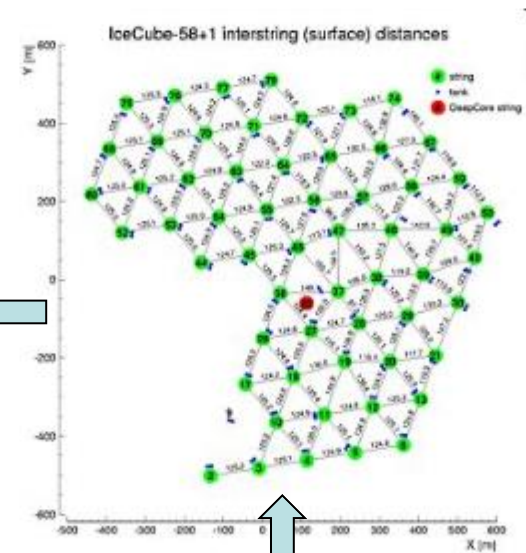
IC86 = full IceCube (2011~)




IC79 (2010-2011)

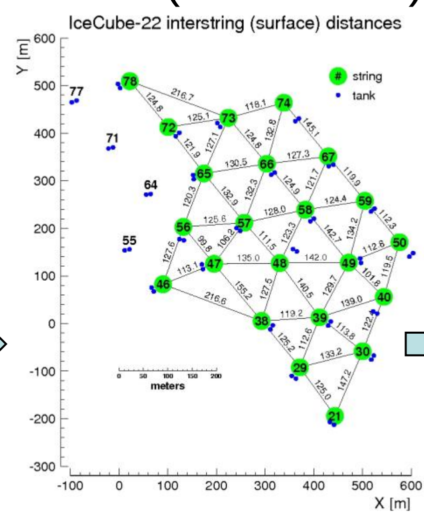



IC59 (2009-2010)

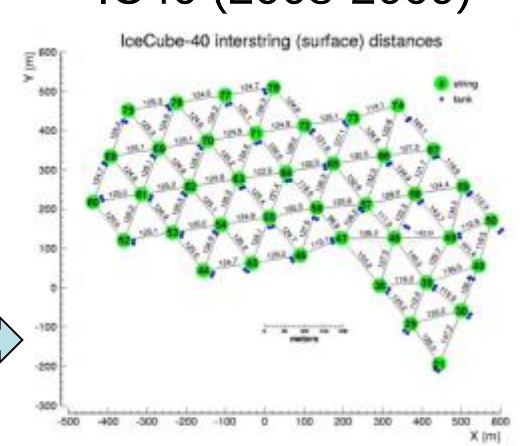



Very stable full operation since May 2011 - Now taking 4th year physics run with the full IceCube configuration

IC22 (2007-2008)

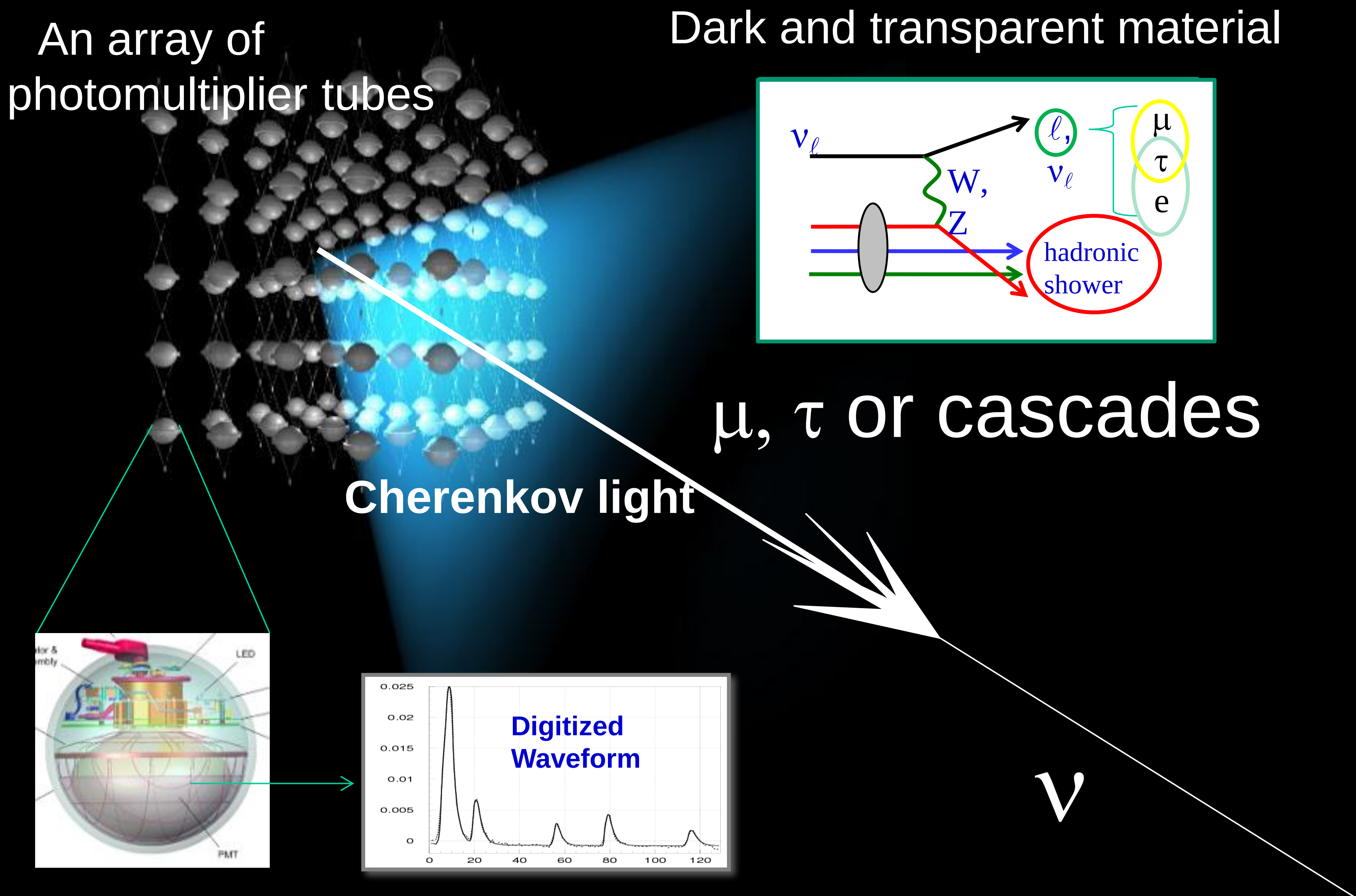



IC40 (2008-2009)

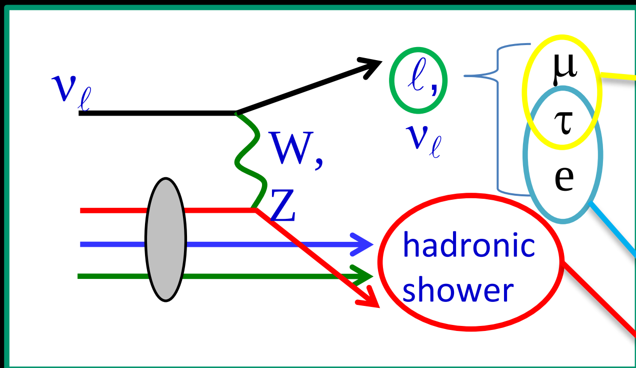



IC9 (2006-2007)
IC1(2005-2006)

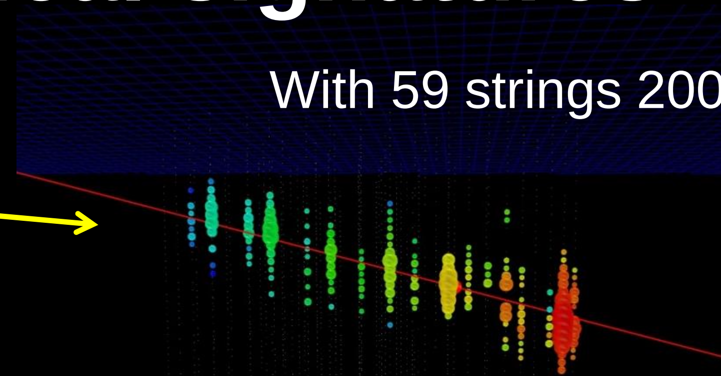
# Detection Principle



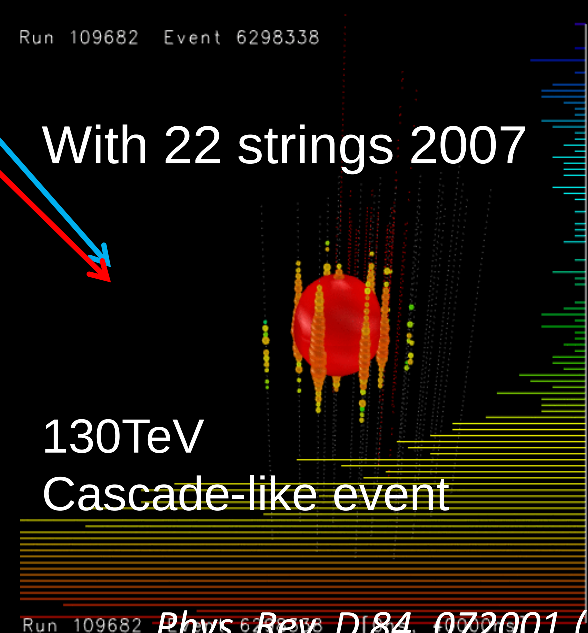
# IceCube event topological signatures




With 59 strings 2009



～100TeV up-going muon
track event

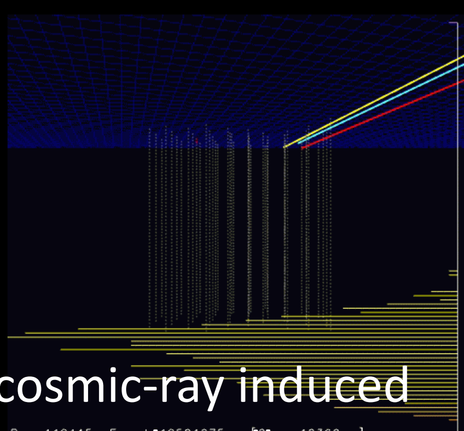



With 22 strings 2007

130TeV
Cascade-like event

*Phys. Rev. D 84, 072001 (2011)*

With 40 strings, 2008 Dec



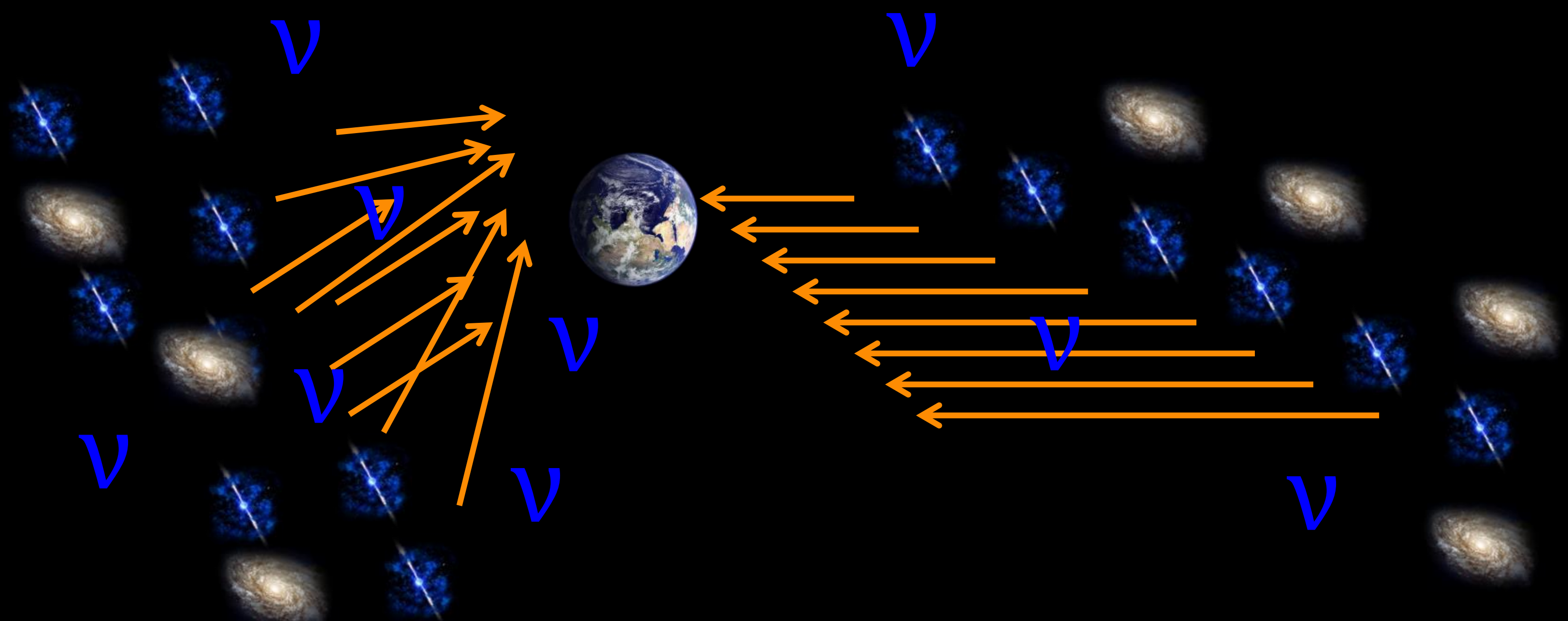

high energy cosmic-ray induced
atmospheric muon bundle event

# Searches for diffuse neutrinos

$$\phi_{\mathrm{diffuse}}(E|L,z) = \int\int\int \phi_{\mathrm{single}}(E|L,z)\,\frac{d^2 n(L,z)}{dz\,dL}\,dz\,dL\,d\Omega$$

**Diffuse neutrino fluxes: Powerful tool to search abandant sources**

- Advantage: Accumulate neutrinos from many many sources even at very far Universe, different direction, and of different types
- Disadvantage: Accumlate background from all the direction and time (good understanding needed), indirect identification of sources

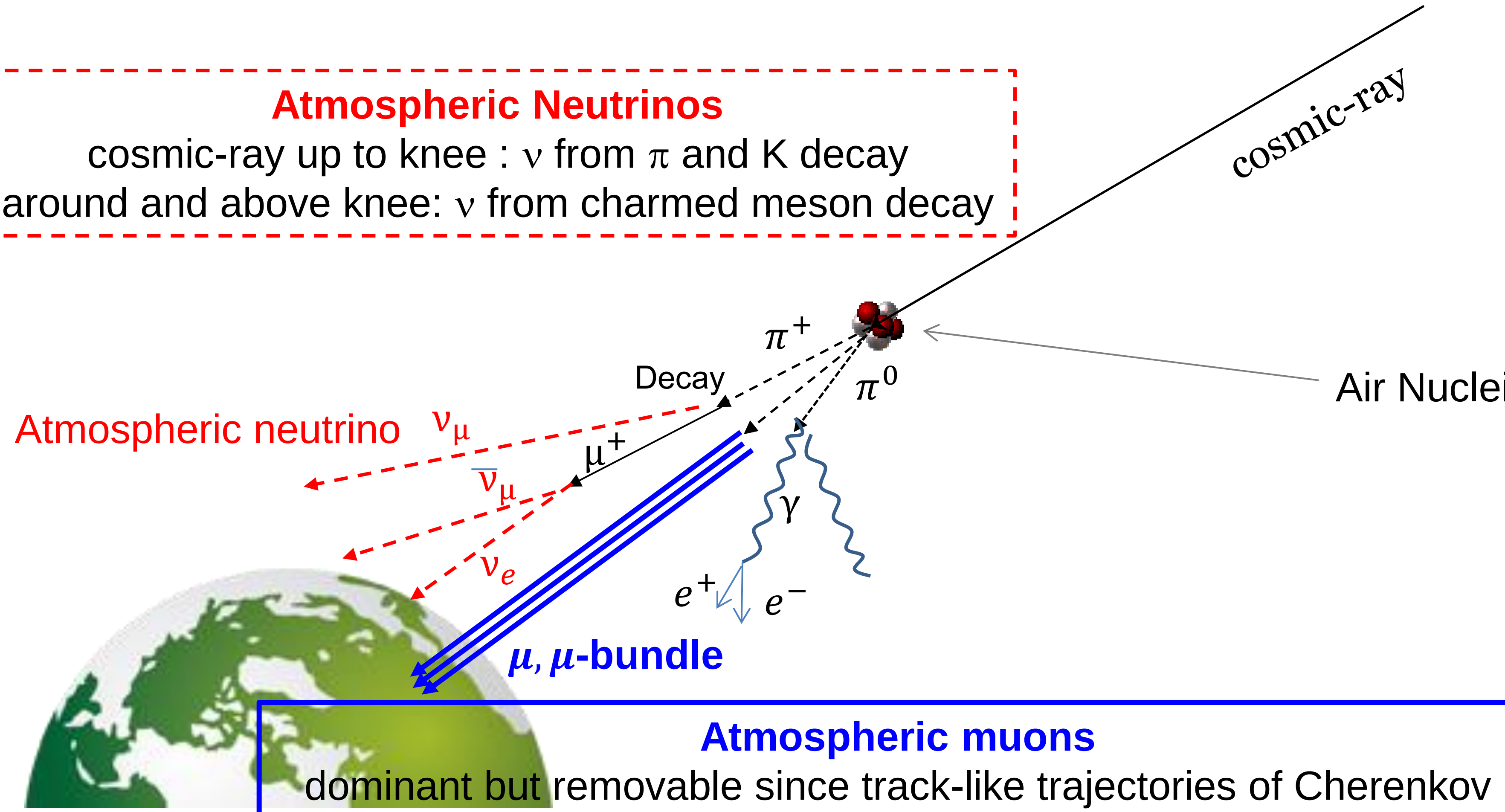


# Background for cosmic diffuse neutrinos

**Atmospheric Neutrinos**

cosmic-ray up to knee : ν from π and K decay

around and above knee: ν from charmed meson decay




**Atmospheric muons**

dominant but removable since track-like trajectories of Cherenkov photons and its directions is able to be reliably reconstructed

# Expected signals in diffuse ν search

**Conventional Atm. neutrinos**
- neutrinos from decays of pions and kaons in atmosphere

**Prompt Atm. neutrinos**
- neutrinos from decays of short-lived mesons in atmosphere

**Astrophysical neutrinos**
- neutrinos from decays of pions in astrophysical sources

"Features" in the energy spectra

steepening of neutrino spectra: $\phi \propto E^{-\gamma}$, conventional **$\gamma$~3.7(+Δ*)** ⇒ prompt **$\gamma$~2.7(+Δ*)** ⇒ astrophysical **$\gamma$~2.0(+α**)**

***Δ is due to cosmic-ray steepening (knee), **α is possible softening at CR acceleration site**

Neutrino "flavor"

flavor changes with energy: conventional $\nu_\mu$ ⇒ prompt $\nu_\mu + \nu_e$ ⇒ astrophysical $\nu_\mu + \nu_e + \nu_\mu$ (?)

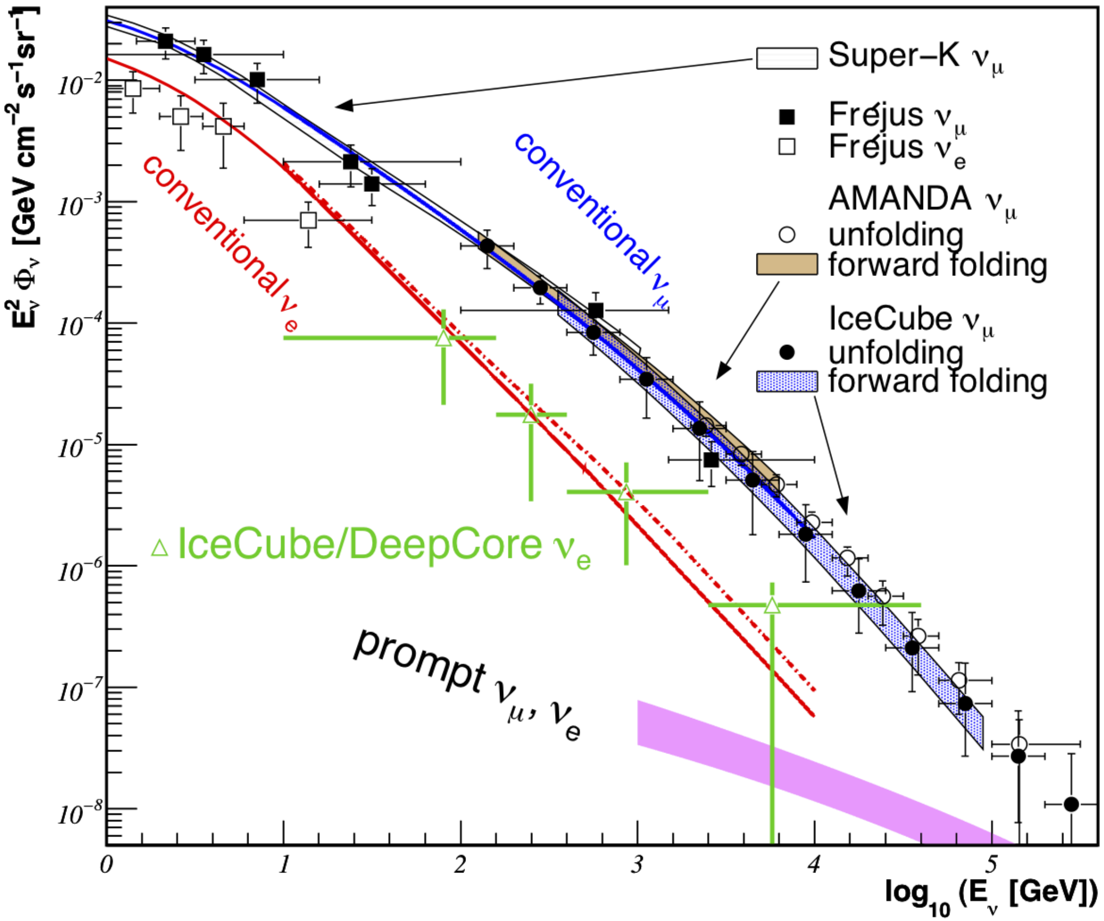
Event "directions"

zenith angle distribution changes with energy:

conventional horizontal enhanced ⇒ prompt isotropic ⇒ astrophysical isotropic (?)

This is true at surface, after propagation in Earth, high energy ν is highly reduced in the upward-going region

# Atmospheric ν measurements



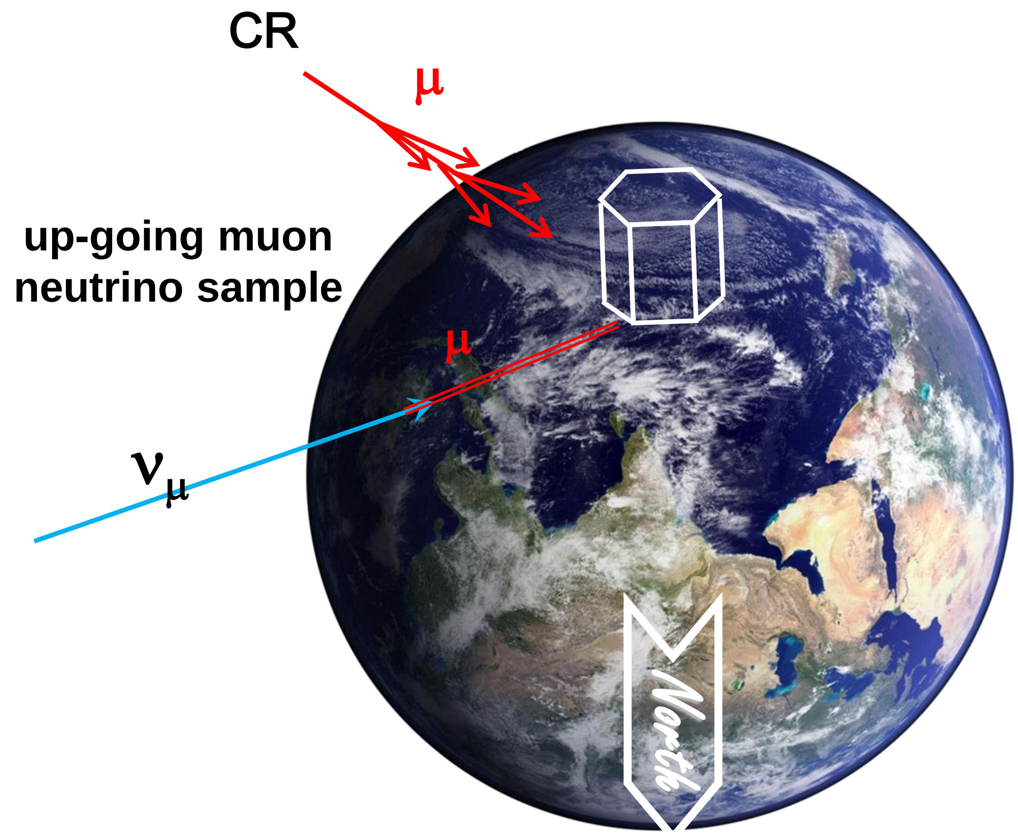

- $\nu_\mu$
- Data: 2008-2009
- ***100 GeV to 400 TeV***

Phys. Rev. D 83, 012001 (2011) by IceCube

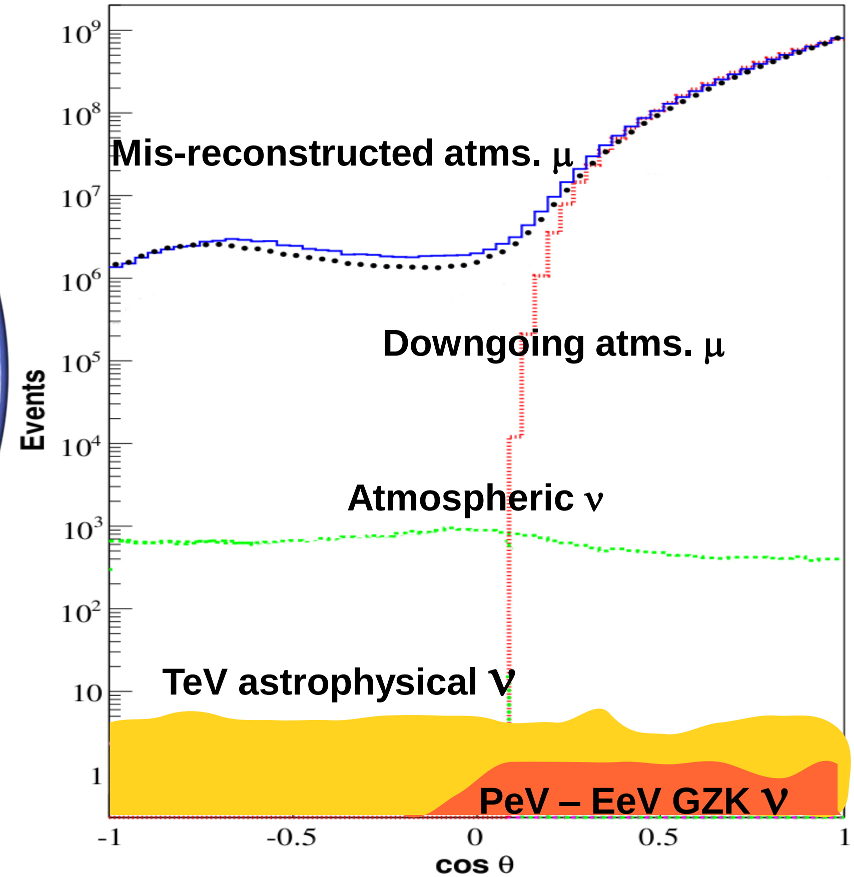
- $\nu_e$
- Data: 2010-2011
- DeepCore
- ***80 GeV to 6 TeV***

Phys. Rev. Lett. 110, 151105 (2013) by IceCube

# Up-Track astrophysical $\nu_\mu$ search

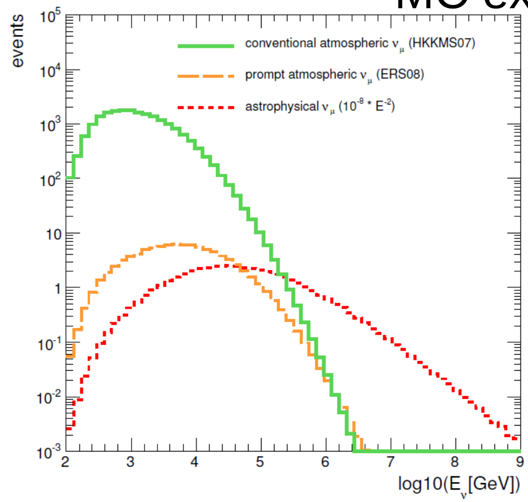


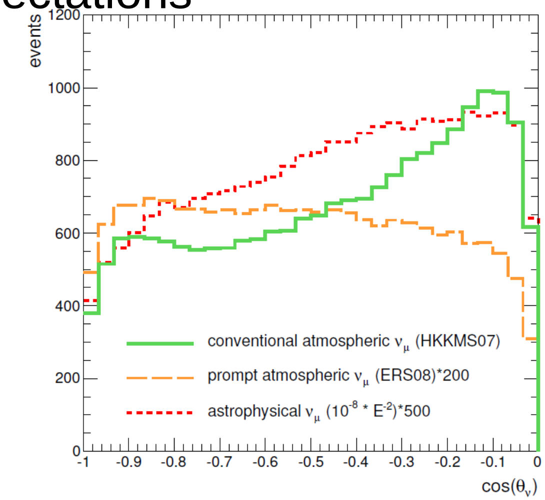

**Trigger rates:**
**Atm. muons: ~3 kHz,**
**~200 atm. ν /day**
**(with E >100 GeV in IceCube)**



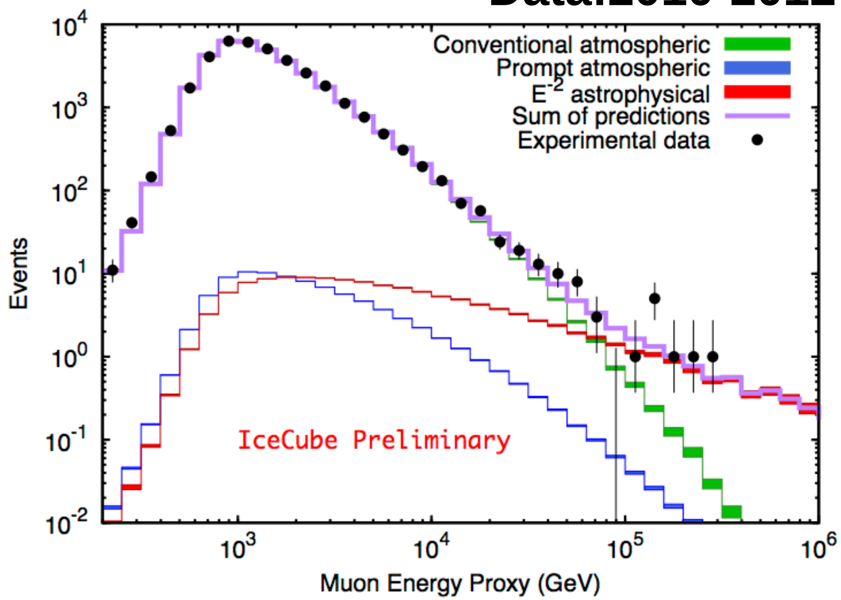
# Astrophysical and Atmospheric $\nu_\mu$

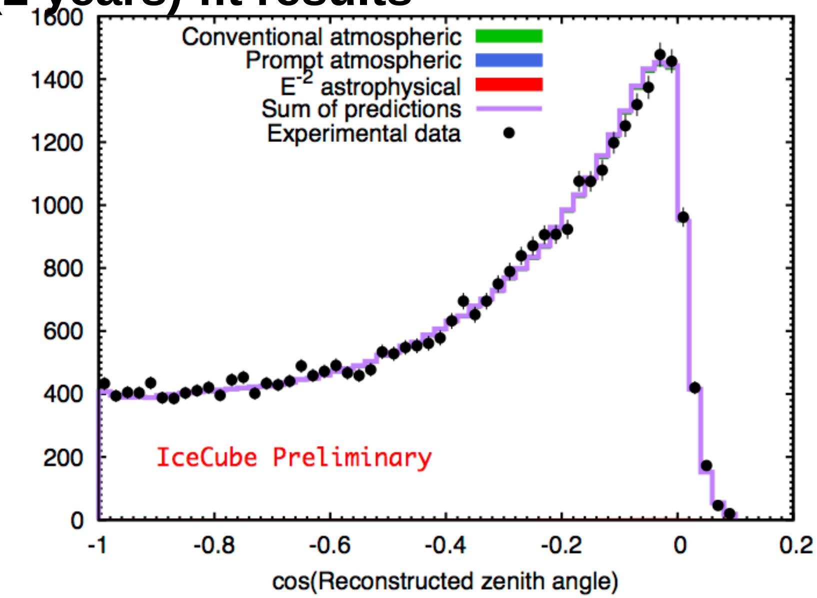
MC expectations




## Data:2010-2012 (2 years) fit results



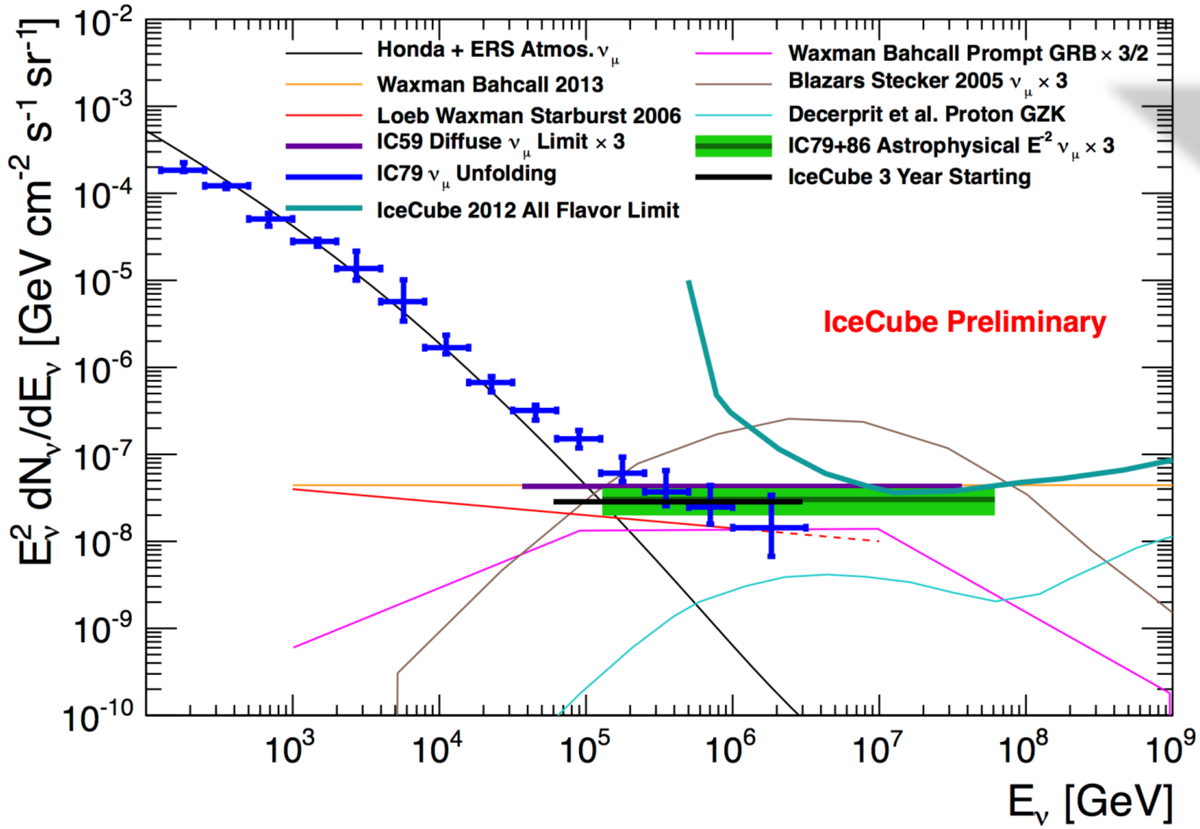



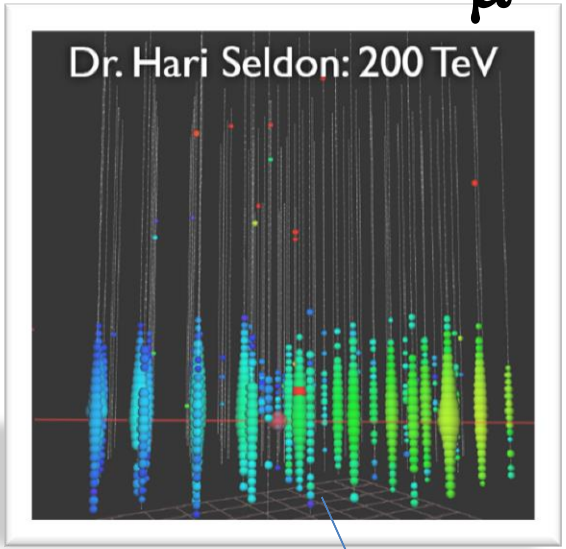
# Extraterrestrial neutrino search with $\nu_\mu$

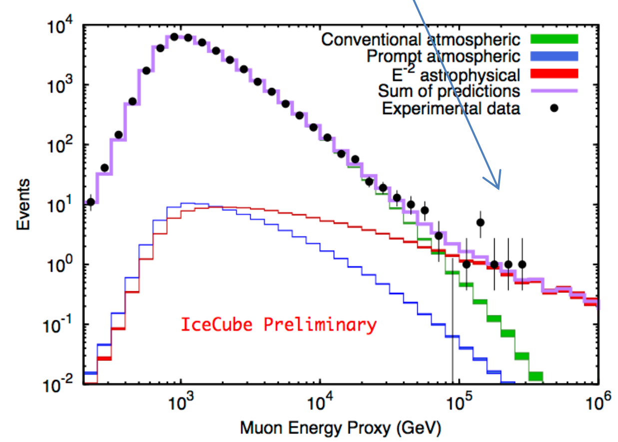
**Data:2010-2012 (2 years)**

- Best fit results of $\phi_{astro} \propto E^{-2}$ for $\nu_\mu$

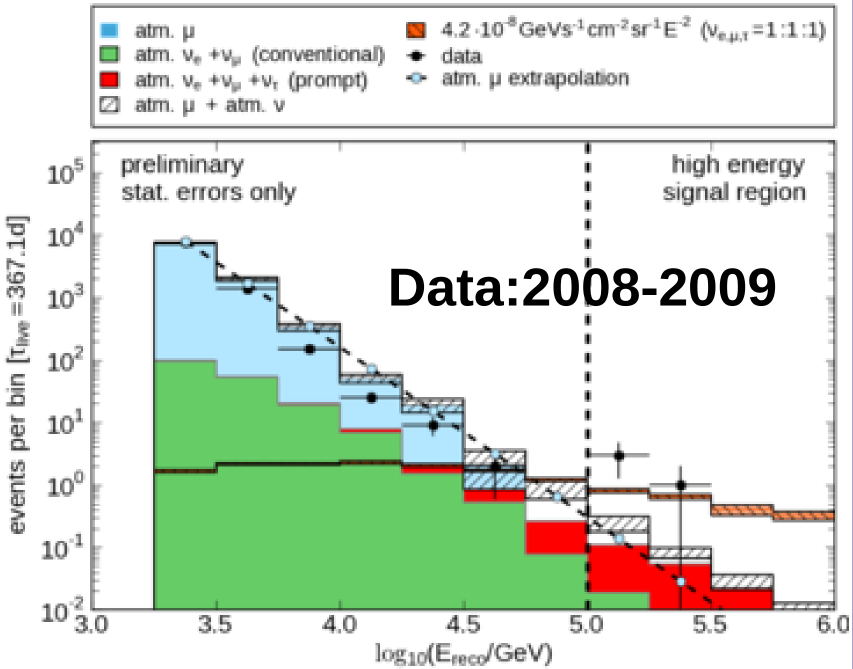
  $E^2\phi=(1.01^{+0.36}_{-034})x10^{-8}$ [GeV cm-1 s-1 sr-1]
- background-only hypothesis disfavored at 3.9σ

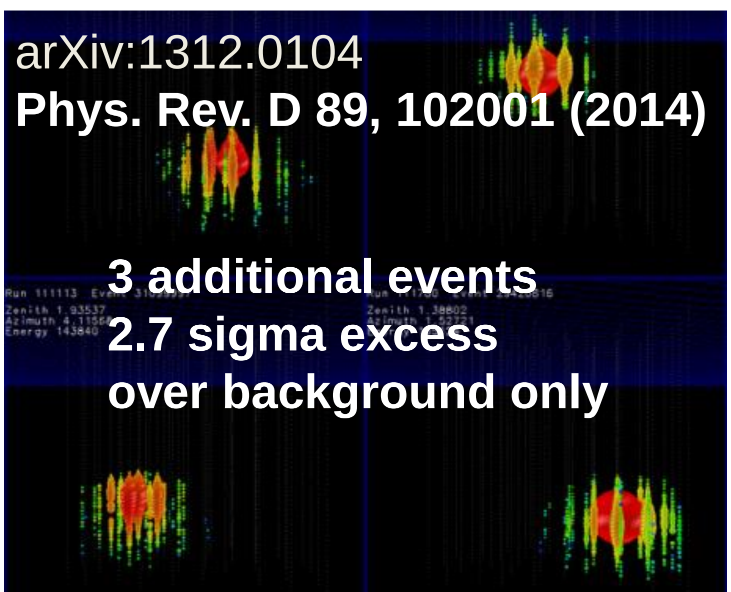


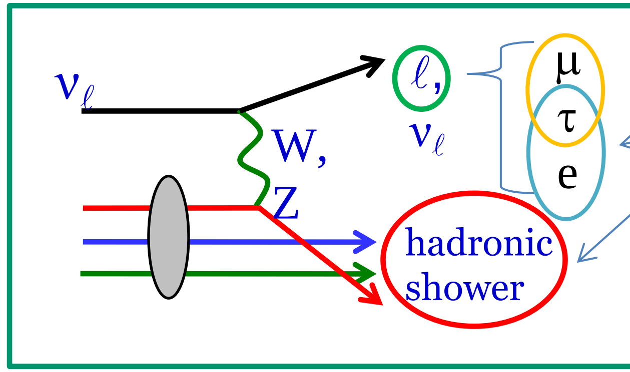



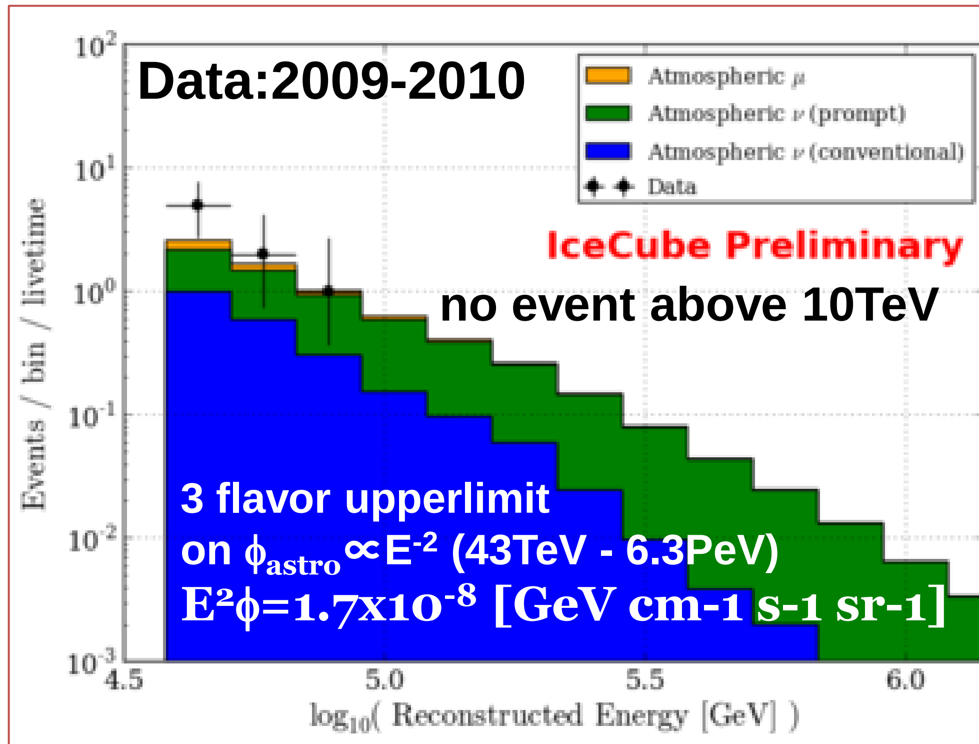
# Extraterrestrial neutrino search with cascades



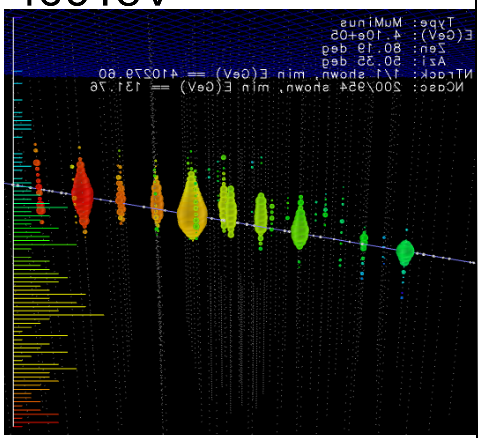

cascade-like signatures



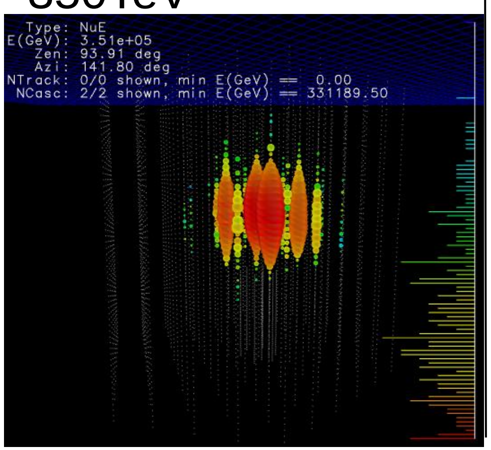
# The extremely high energy neutrino search

**below ~PeV, upward-going tracks and cascade-like topology is important**

400TeV

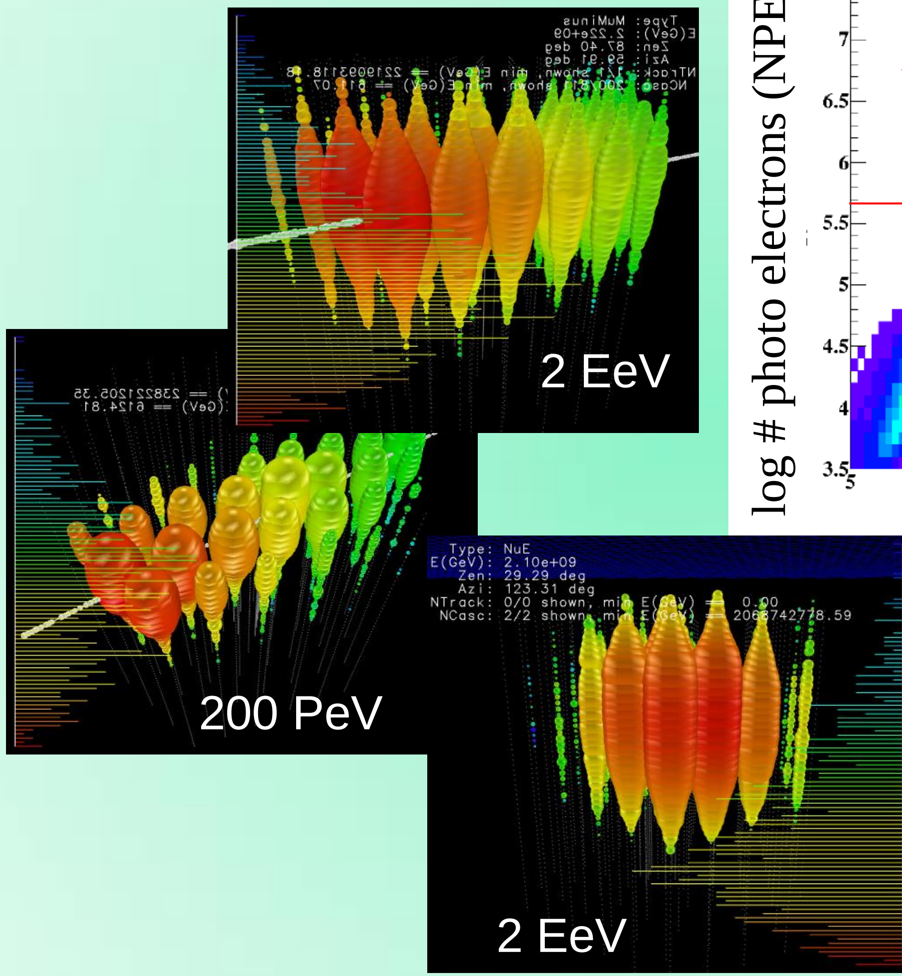


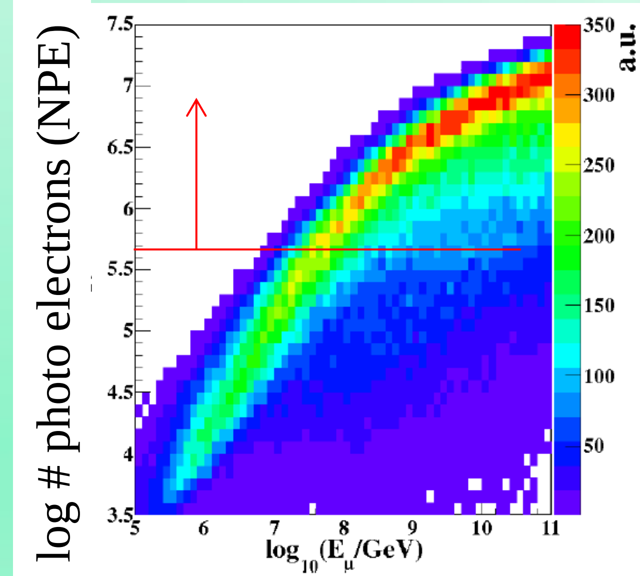
350TeV




**'Very bright' is an important condition**

Select both type of events with a 'brightness' of events



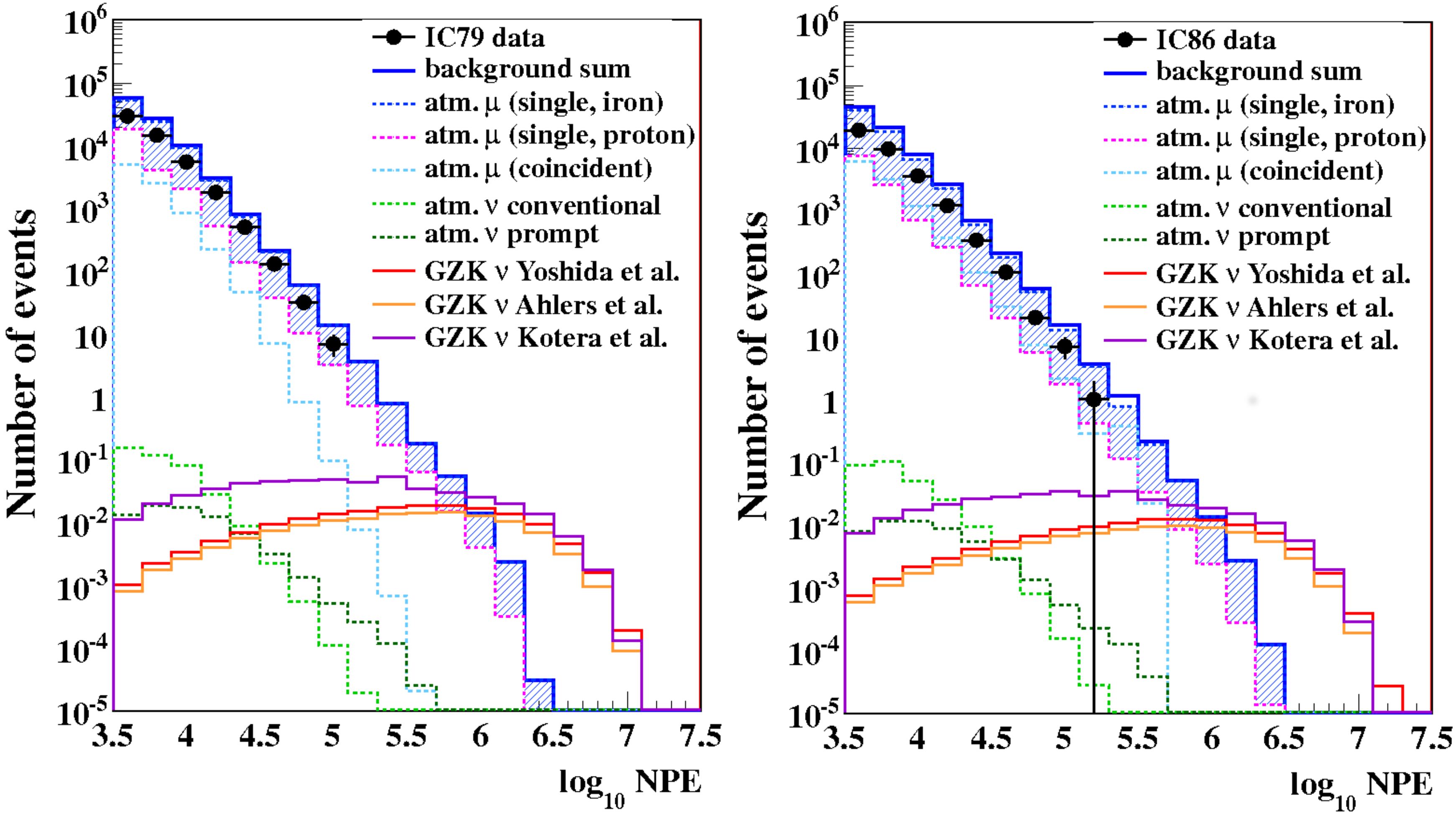




from MC simulation

# IceCube EHE Event NPE Distributions

*PhysRevD.88.112008 (2013)*

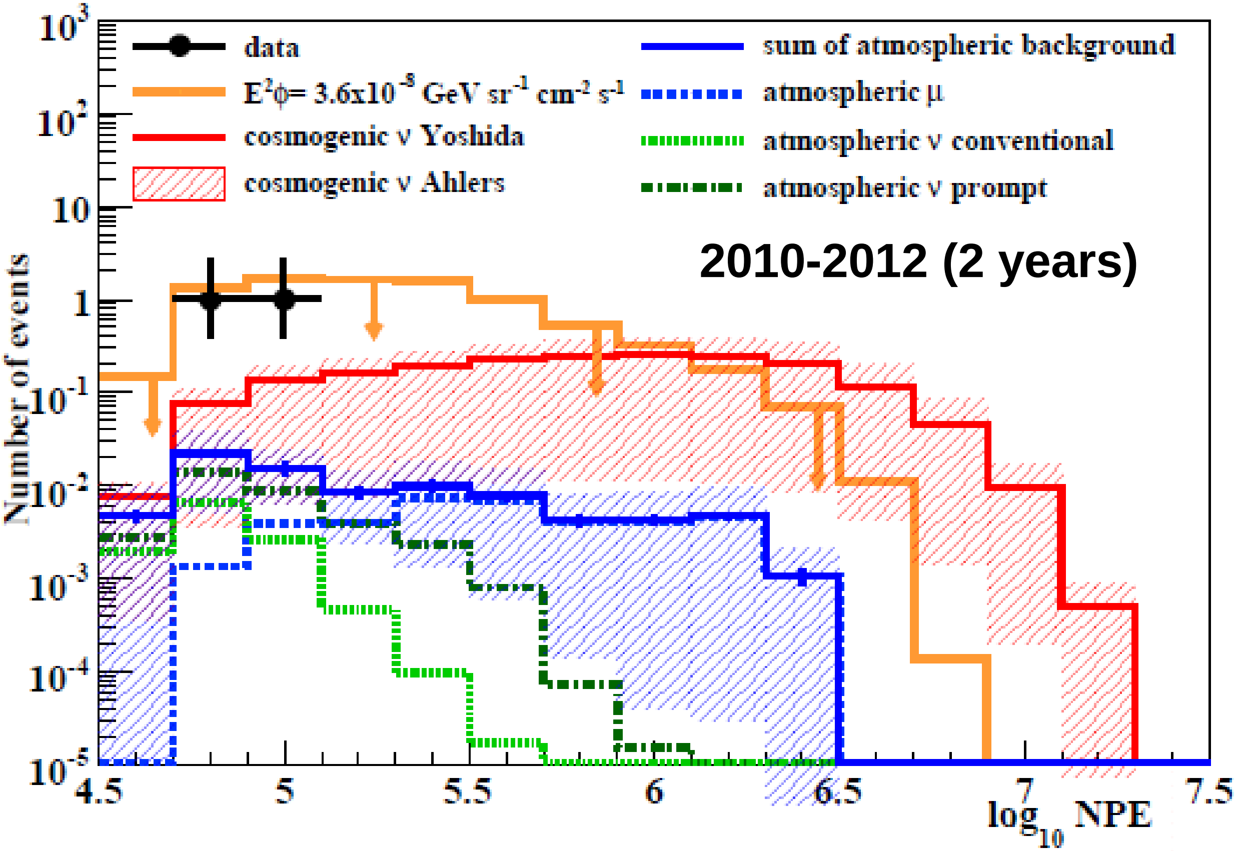
NPE > 3000 (10% test sample)

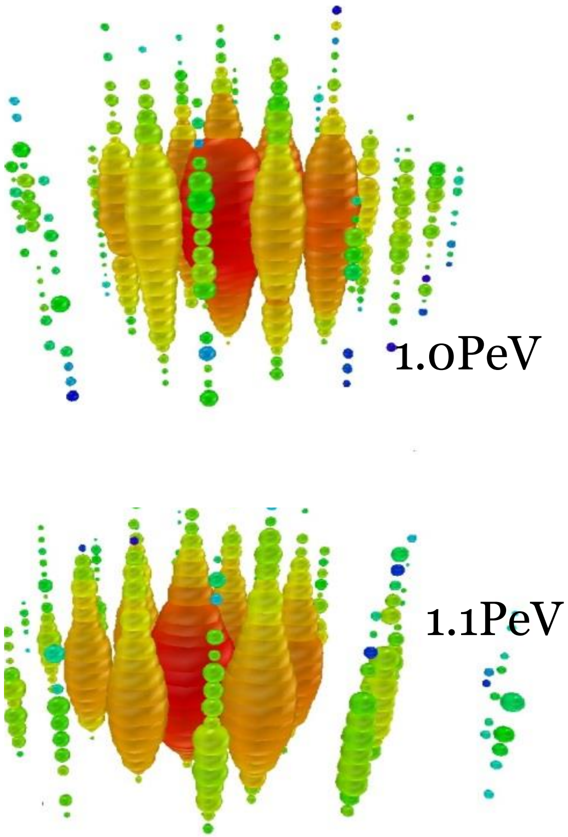


# Extremely high energy neutrino search above PeV

Phys. Rev. Lett. 111, 021103 (2013)

- 2..8sigma excess over $0.08^{+0.04}_{-0.06}$ events of default atmospheric background




Number of photoelectrons: NPE ∝ Visible Energy

Aya Ishihara KEK at Tokai

# Are these 2 events cosmogenic in origin?

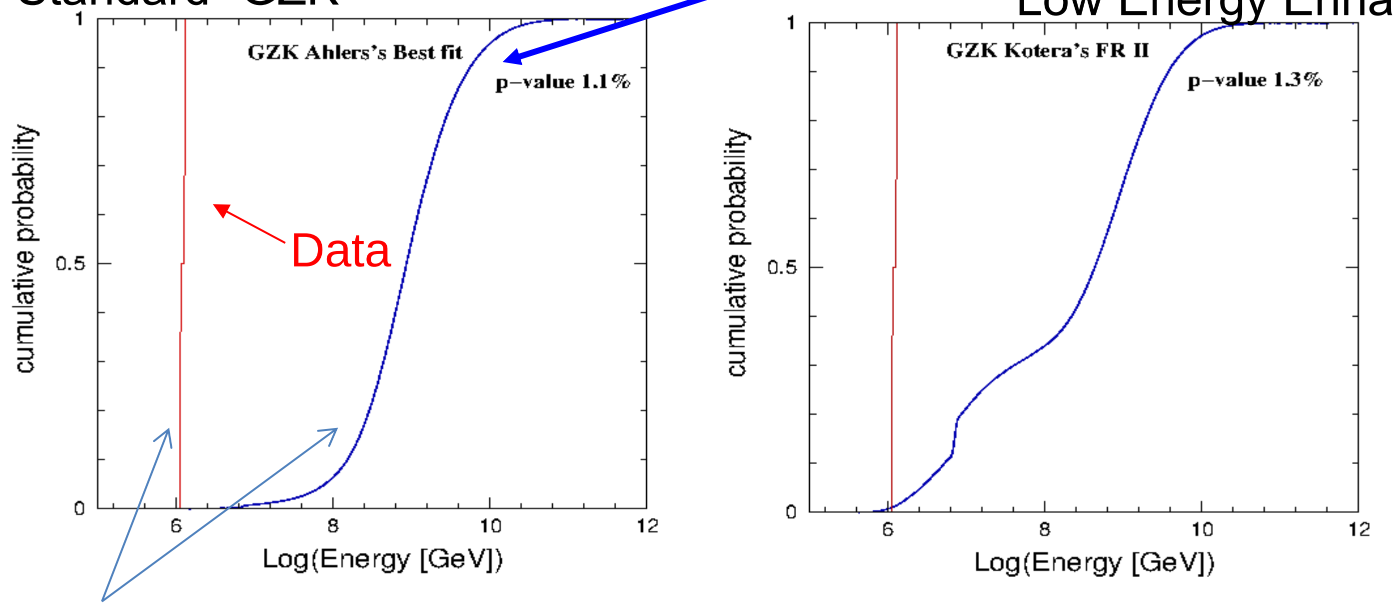
the Kolmogonov-Smirnov test implies that the estimated energies (assuming GZK spectra on surface) can not be explained by the cosmogenic neutrino models

**No!**

The predicted $E_\nu$ cumulative probability

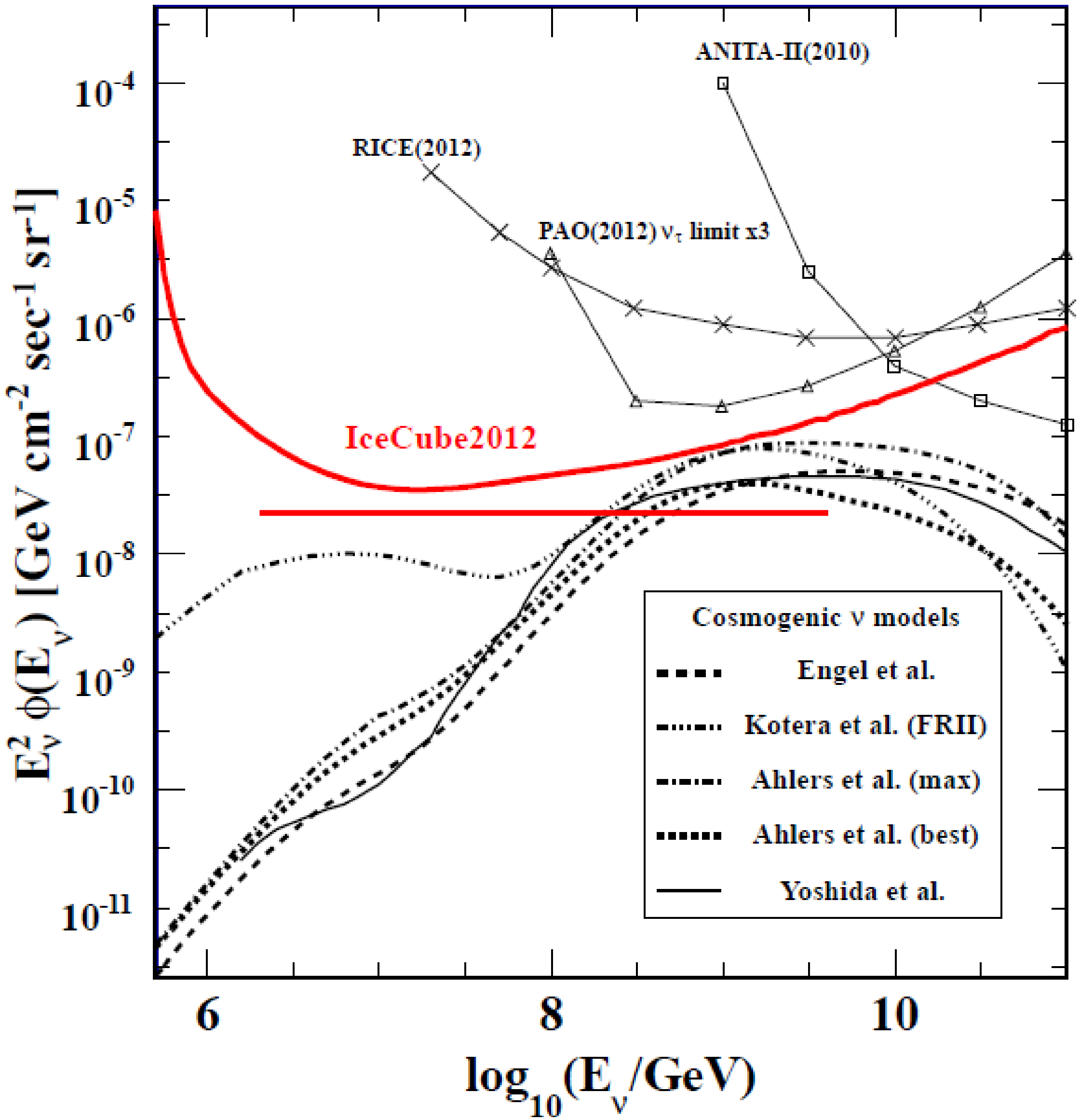
"Standard" GZK

"Low Energy Enhanced" GZK




The test tells that they are very (at 90%CL) inconsistent

# Model independent quasi-differential upper limit

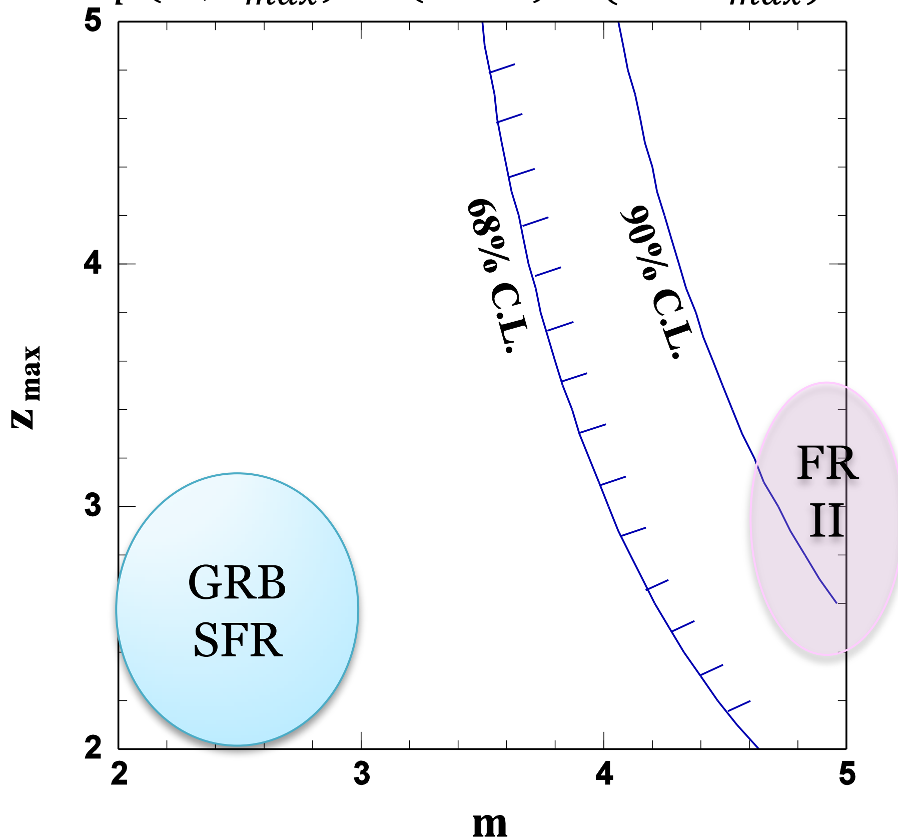



- Including Energy PDF of the two events
  - PeV region upperlimits are weaken by the 2 event observation
- Significantly improved from the previous upperlimits
- IceCube becoming more and more sensitive to cosmogenic fluxes above ***100 PeV ($10^8$ GeV)*** and started to constrain the highest energy comsic-ray source evolutions
- $E^{-2}$flux integrated limit taking into 2 observations

$E^2\varphi(\nu_e+\nu_\mu+\nu_\tau)= 2.5\times10^{-8}$GeV cm$^{-2}$s$^{-1}$sr$^{-1}$(1.6 PeV – 3.5 EeV)

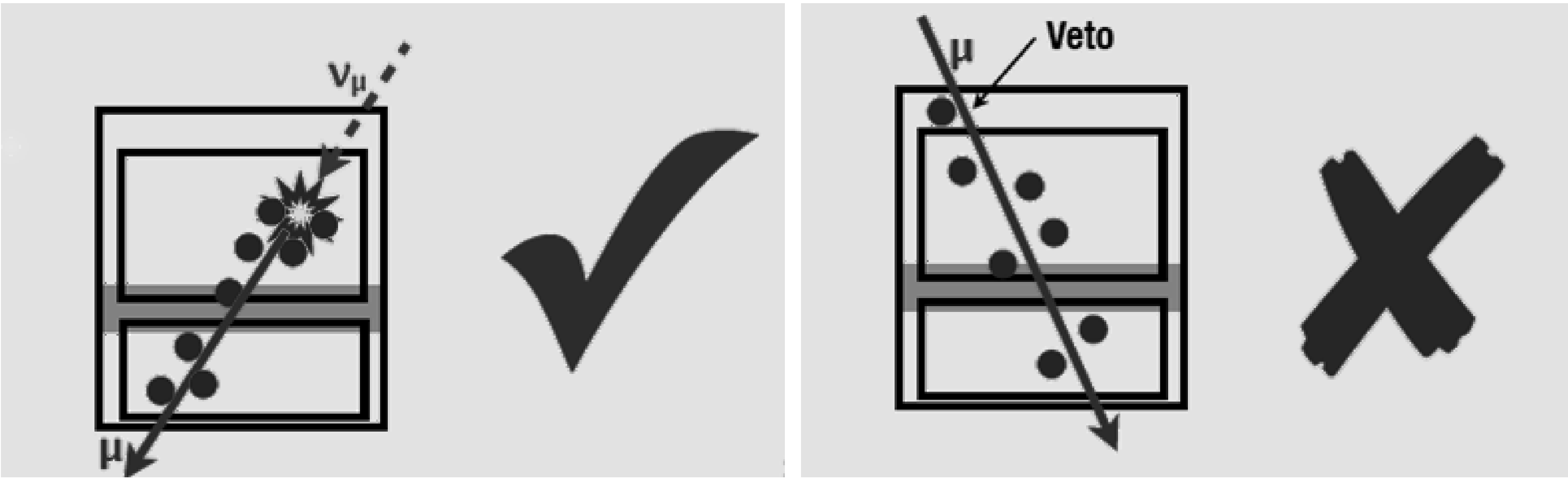
# Constraint on the highest energy neutrino fluxes and cosmic-ray sources

$p(m, z_{max}) = (1+z)^m \; (z < z_{max})$



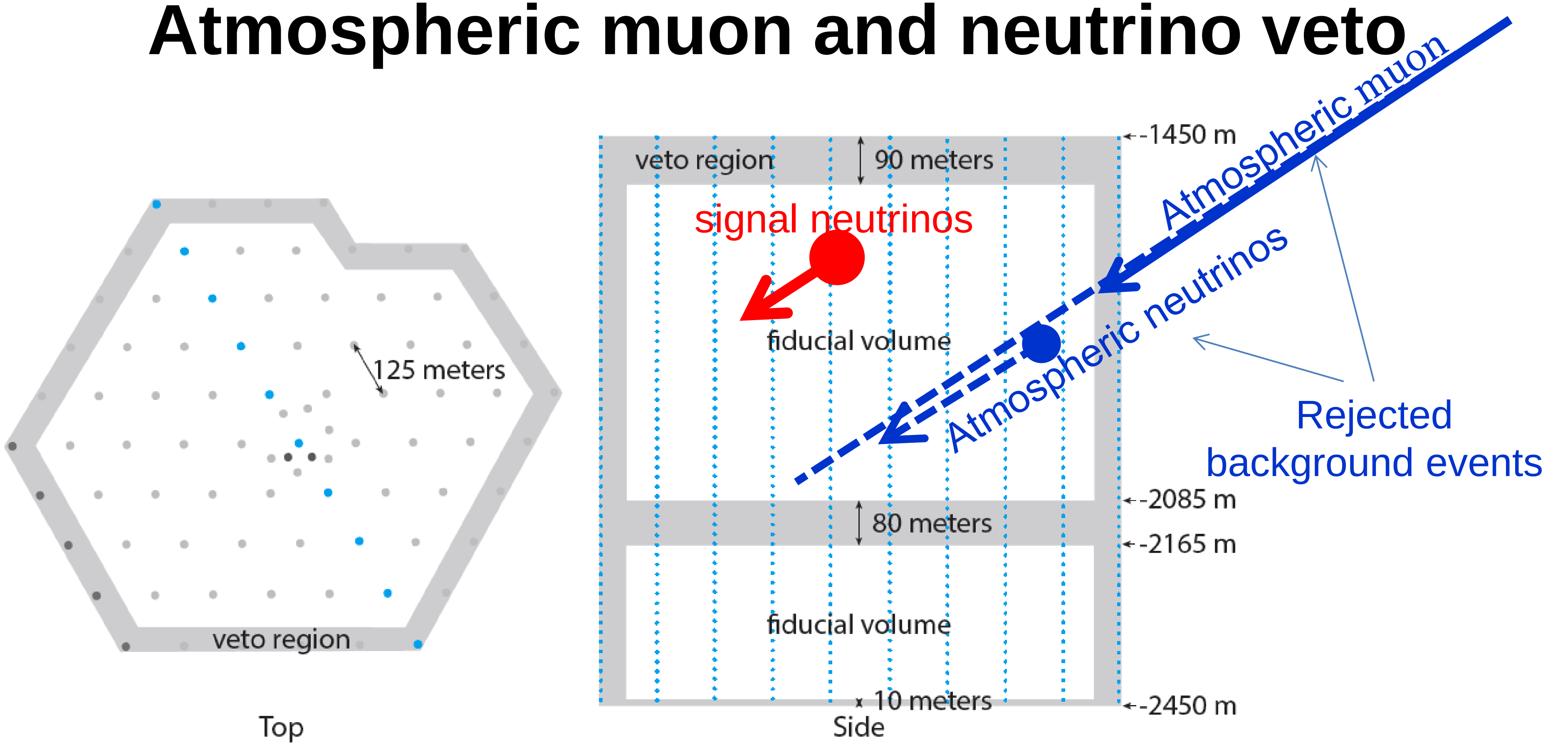

- Highly evoloving source models of the highest energy cosmic-ray protons can be excluded
- Disfavoring a generic expression of the evolution parameter m larger than ~4 which includes radio loud active galaxies (FRII)

# High Energy Starting Event Analysis




- **Followup analysis on the UHE cascade-like events**
- **Atmospheric muon/neutrino background largely reduced by vetoing events with initial photons in outer layers**
- **Events with NPE > 6000 (the case for EHE, NPE > 60000), sensitivity extended down to 30TeV**

# Atmospheric muon and neutrino veto

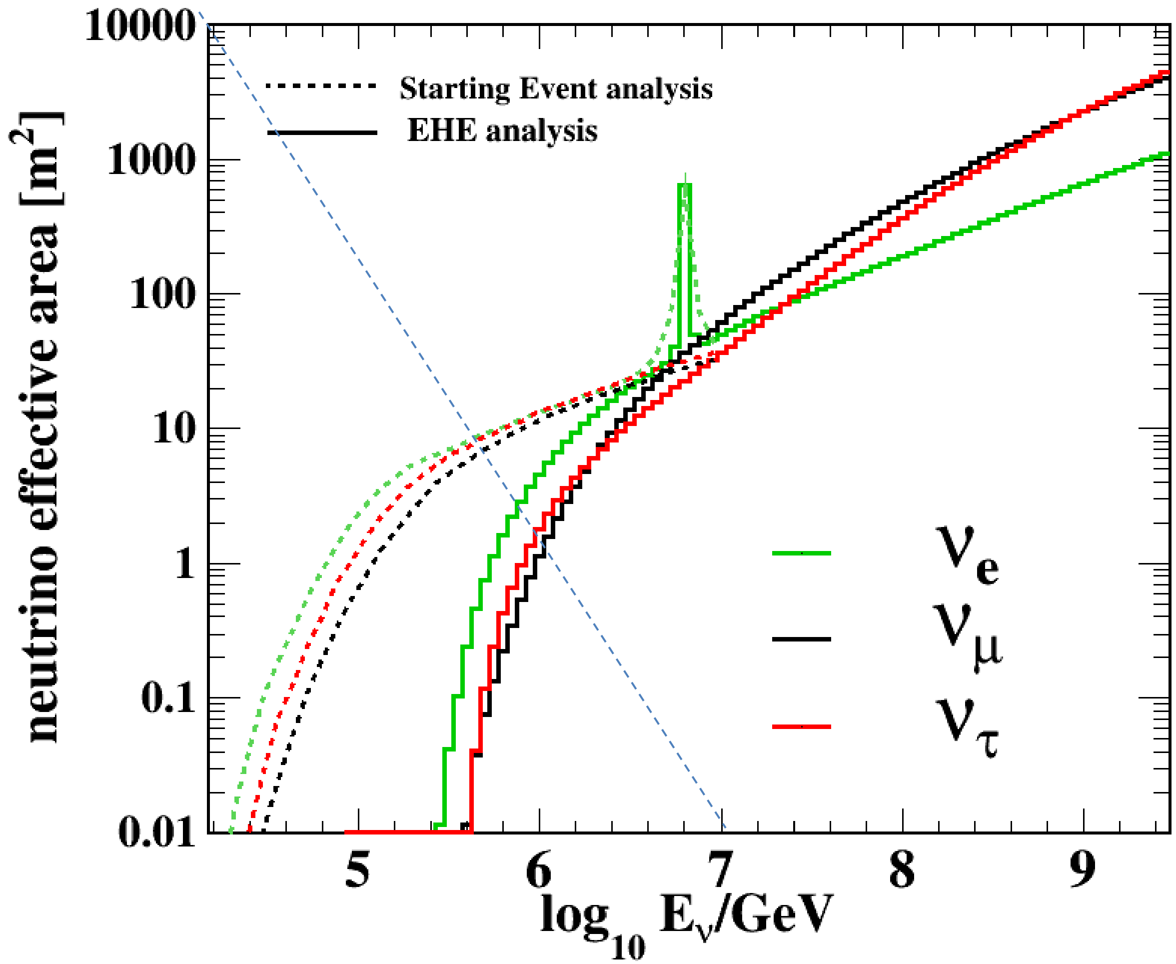



- Down-going atmospheric neutrinos are also reduced by vetoing atmospheric muon events
- **This changes atmospheric neutrino zenith angle distributions to upward-going dominated**

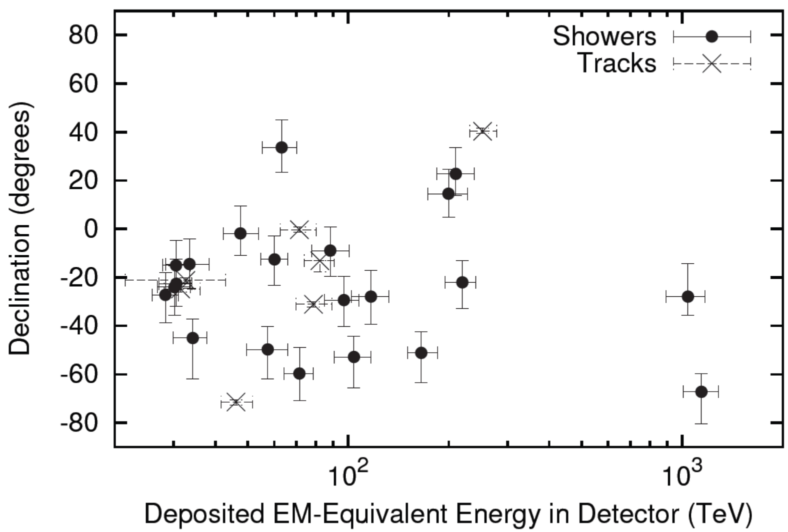
# Effective Areas

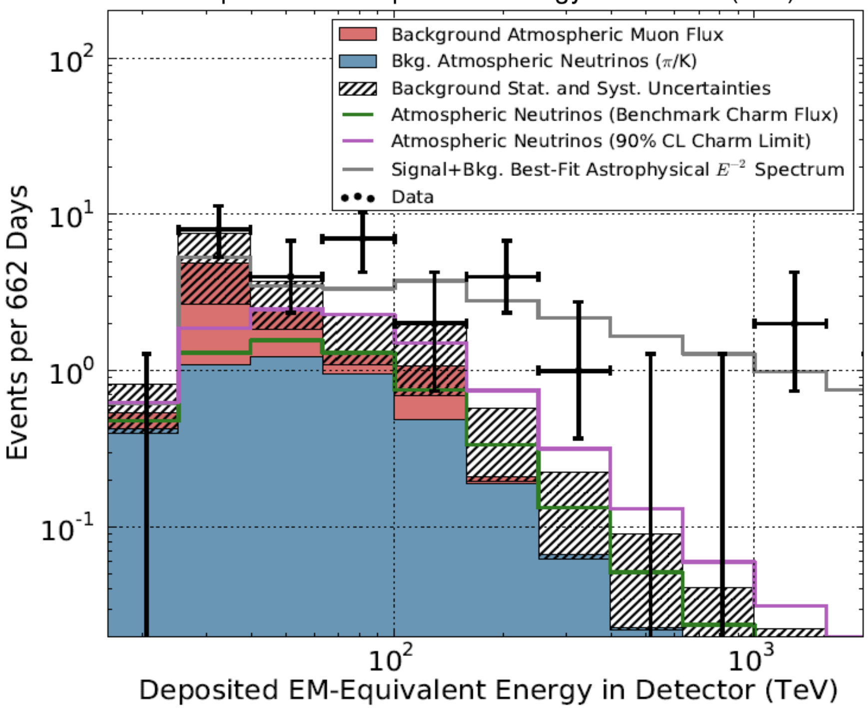
Propositional to expected event rates

Area x $\nu$ flux x $4\pi$ x livetime = event rate



# Starting event energy distribution




**<u>IceCube:</u>**
**<u>Science 342, 1242856 (2013)</u>**

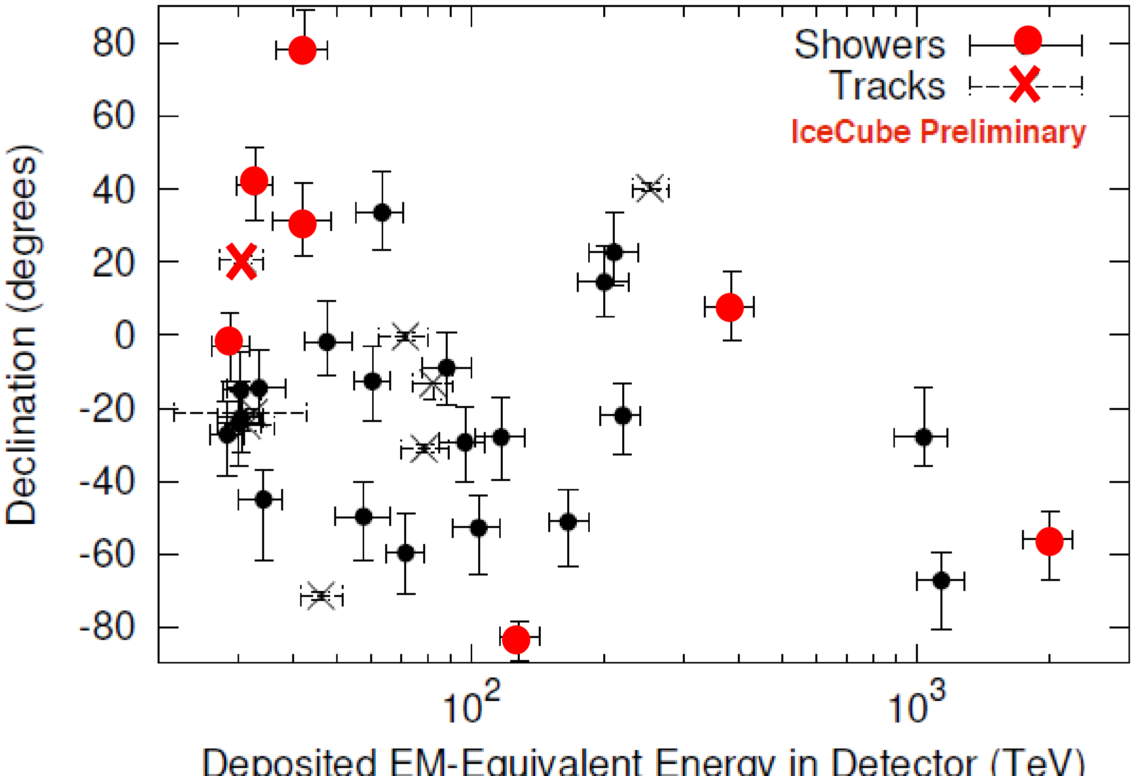
**2010-2012 (2 years) results**

- 26 new events found
  (19 cascades, 7 with tracks)
- over background expectation of $10.6_{-3.6}^{+5}$ total atmospheric muons (6.0 ±3.4) and atmospheric neutrinos ($4.6_{-1.2}^{+3.7}$)
- **Best fit results**
  $E^2\phi$=(1.2±0.4)x10-8 [GeV $cm^{-2}$ $s^{-1}$ $sr^{-1}$] with a hard cut off at 1.6PeV

# Starting Events in 3 year sample

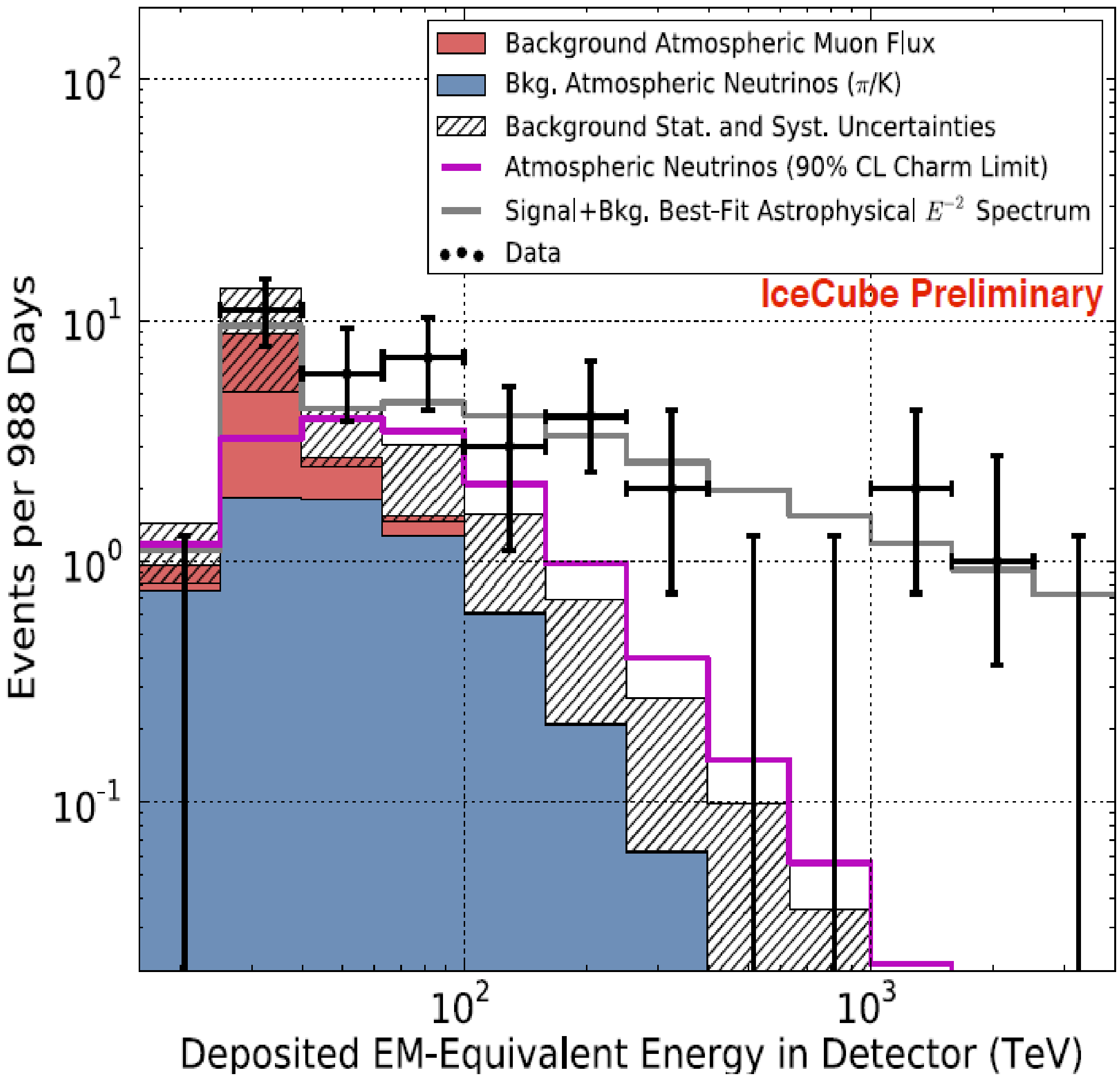
**2010-2013 (3 years)**

Physical Review Letters 113 (2014) 101101;
arXiv:1405.5303




- 9 new events found
- 7 cascades, 1 with tracks, and 1 coincident muon event (not plotted)
- 5 from southern sky and 3 from northern sky
- the highest energy 2PeV event in the test sample
- 28+9 over background expectation of $15.0^{+7.2}_{-4.5}$ atmospheric muons $8.4 \pm 4.2$ and atmospheric neutrinos $6.6^{+5.9}_{-1.6}$

# Extraterrestrial neutrino search with starting events

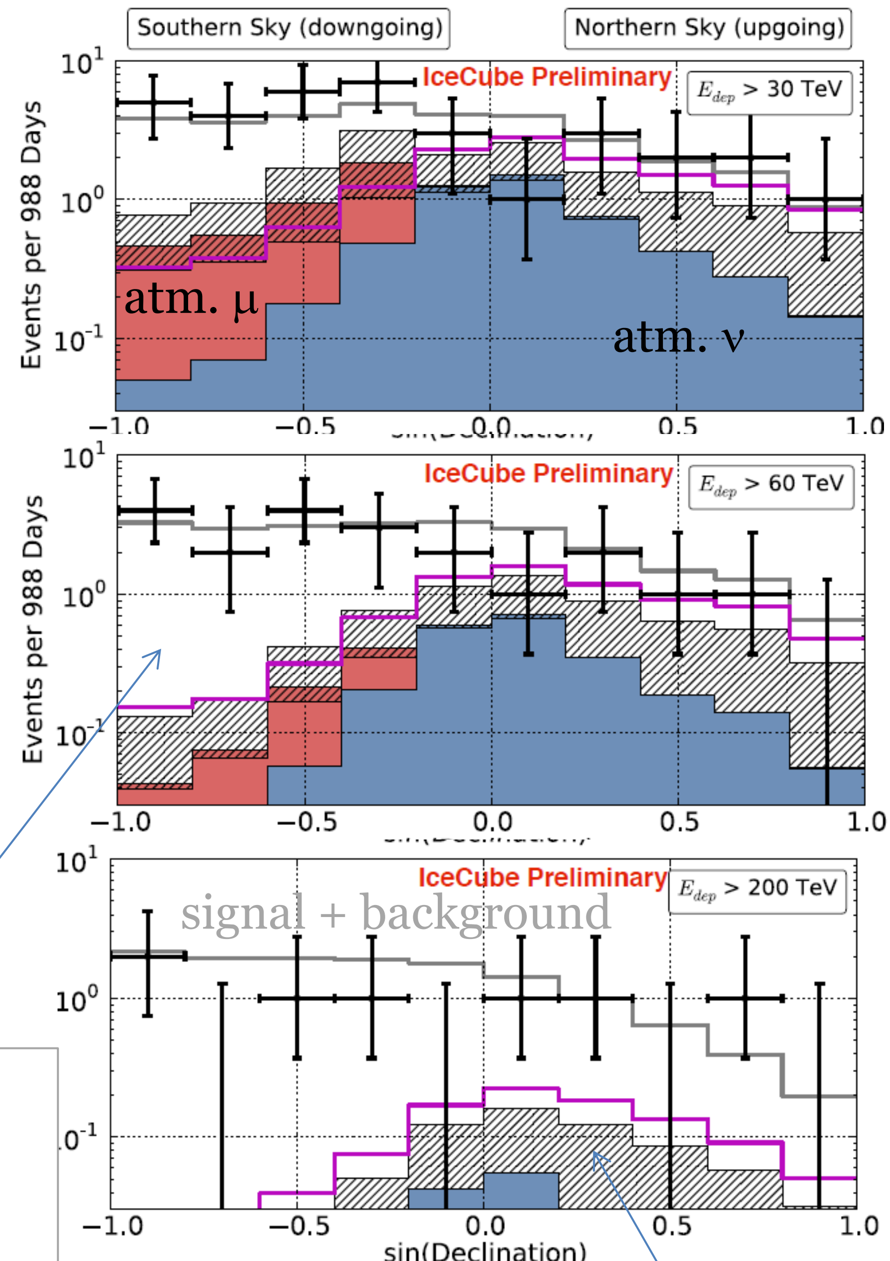



- atmospheric background $13.0^{+7.2}_{-4.5}$
- **Inconsistent with background only model** at 4.1σ with 28 events (science 2013) and 5.7σ with additional 7 events (preliminary)
- Event features (reconstructed energy, zenith angle and topology) **consistent with background + astrophysical ($\phi_{astro} \propto E^{-2}$) fluxes**

- **Best fit flux** $E^2\phi=(0.95\pm0.3)\times10^{-8}$ [GeV $cm^{-2}$ $s^{-1}$ $sr^{-1}$] with a hard cut off around 2.0 PeV or a softer spectra with a spectral index $\gamma=2.3\pm0.3$

# Zenith angle distributions

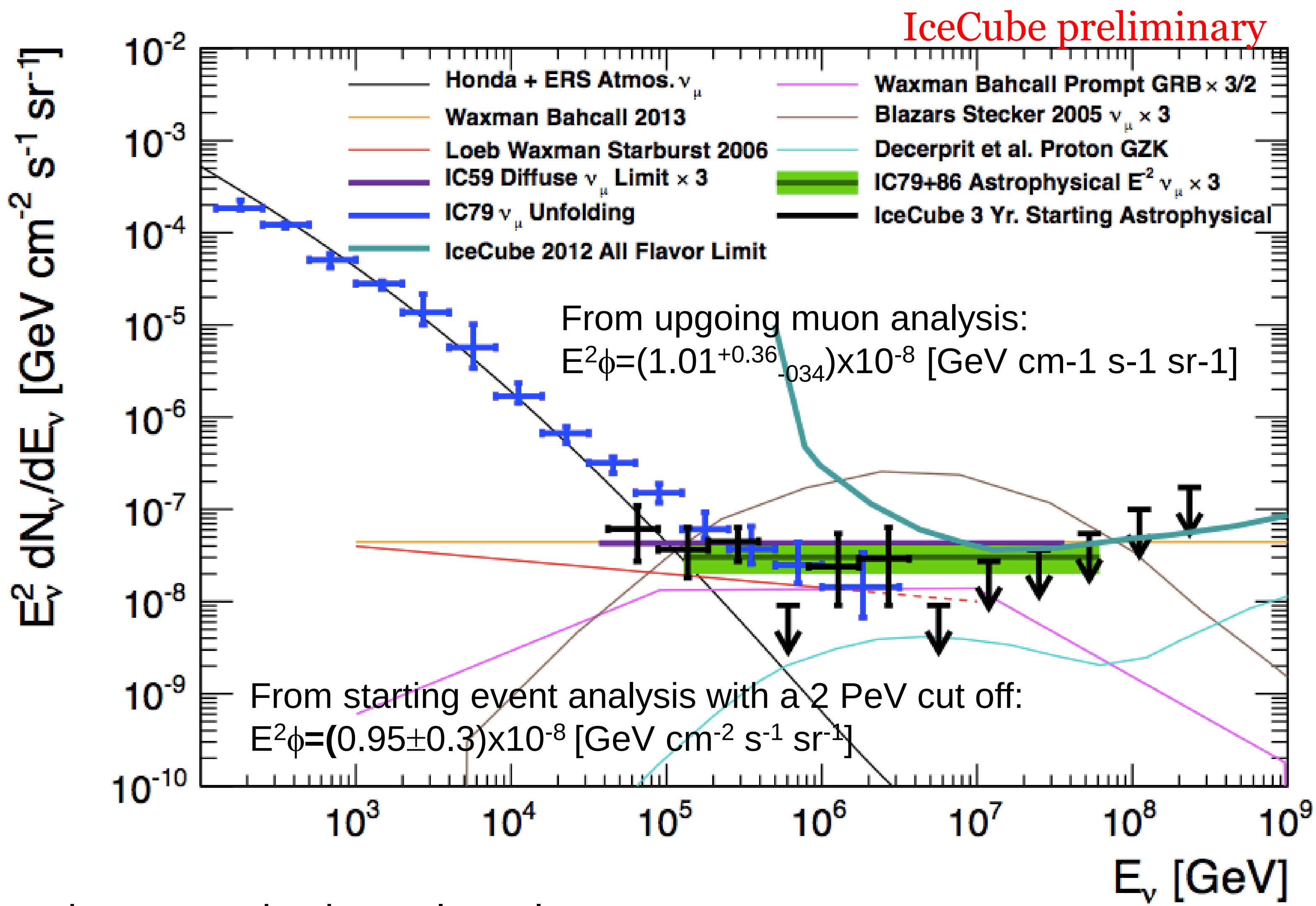
- Low energy atmospheric muons in downward-going geometry
- Atmospheric neutrinos in horizontal to upward-going region
- High energy astrophysical component dominant in the downward-going region




Veto method suppress a large fraction of southern atmospheric neutrino background but not the astrophysical neutrinos

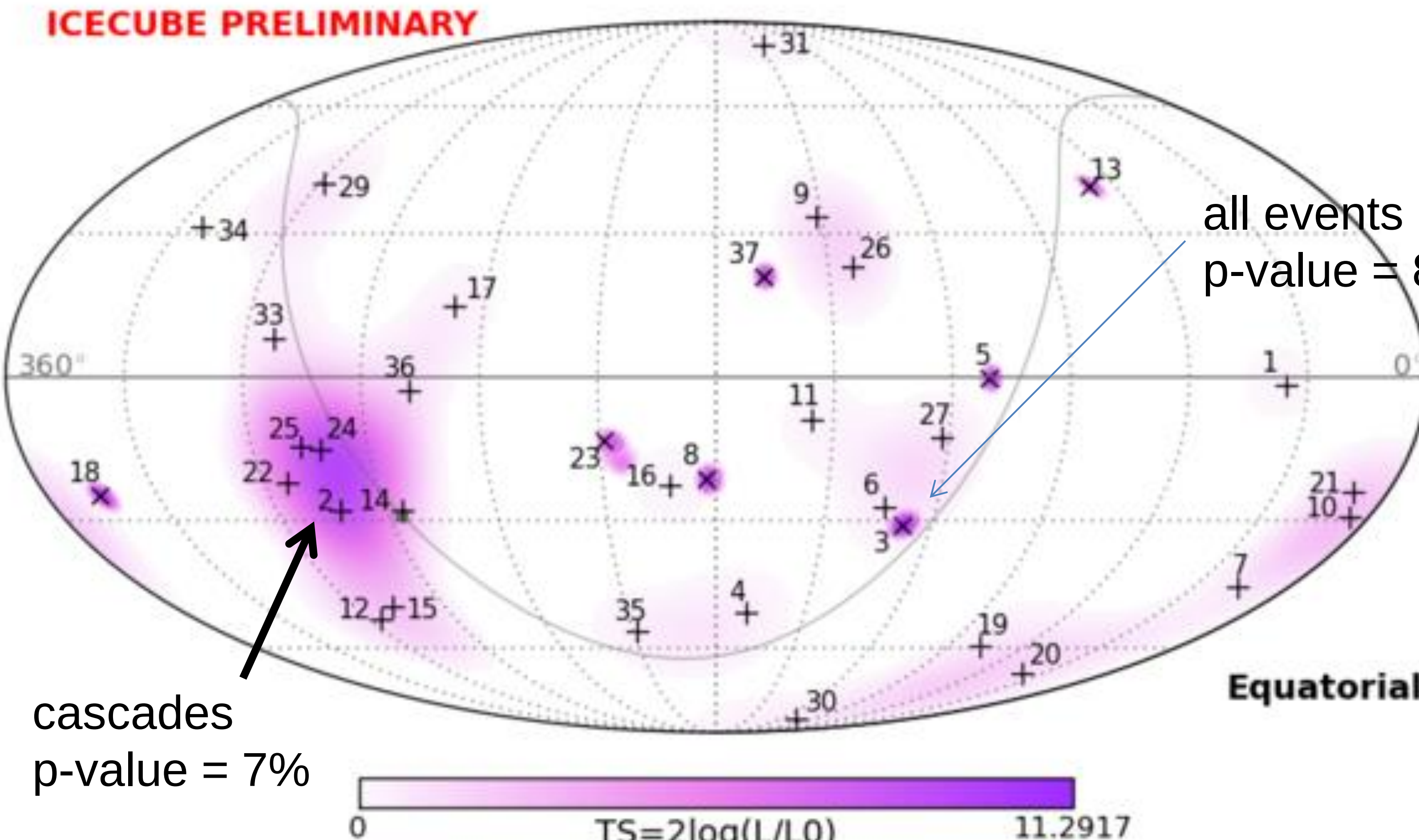
background systemic uncertainty

# Diffuse neutrino flux summary




2 years data cascade channel results soon to come

# High energy starting event clustering




all events
p-value = 84%

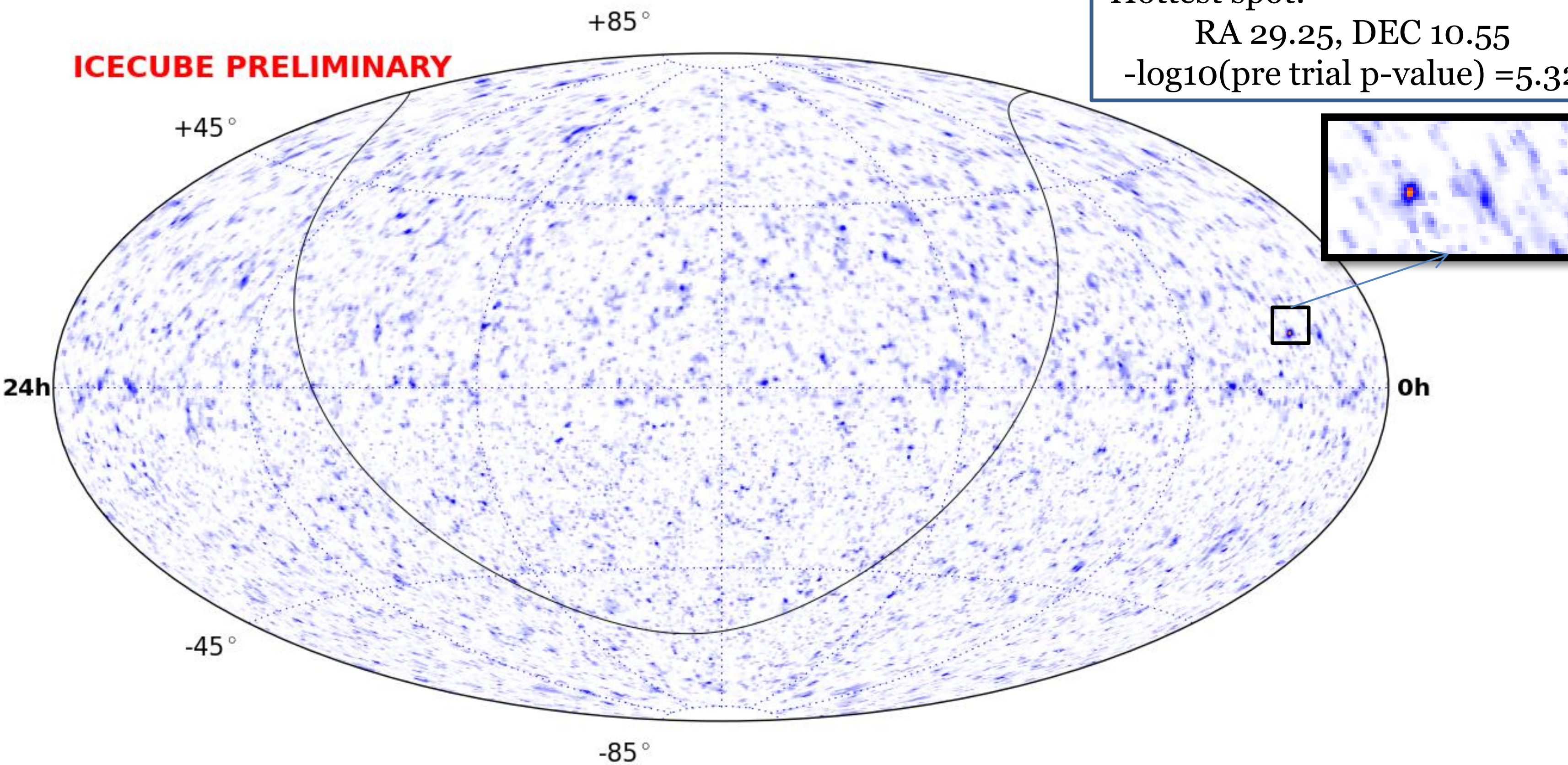
cascades
p-value = 7%

No evidence of (significant) spatial clustering

# More quests for ν point sources

- all-sky through-going muons unbinned point source analysis
- 4 years (IC40+IC59+IC79+IC86) 1373days

Hottest spot:
RA 29.25, DEC 10.55
-log10(pre trial p-value) =5.32



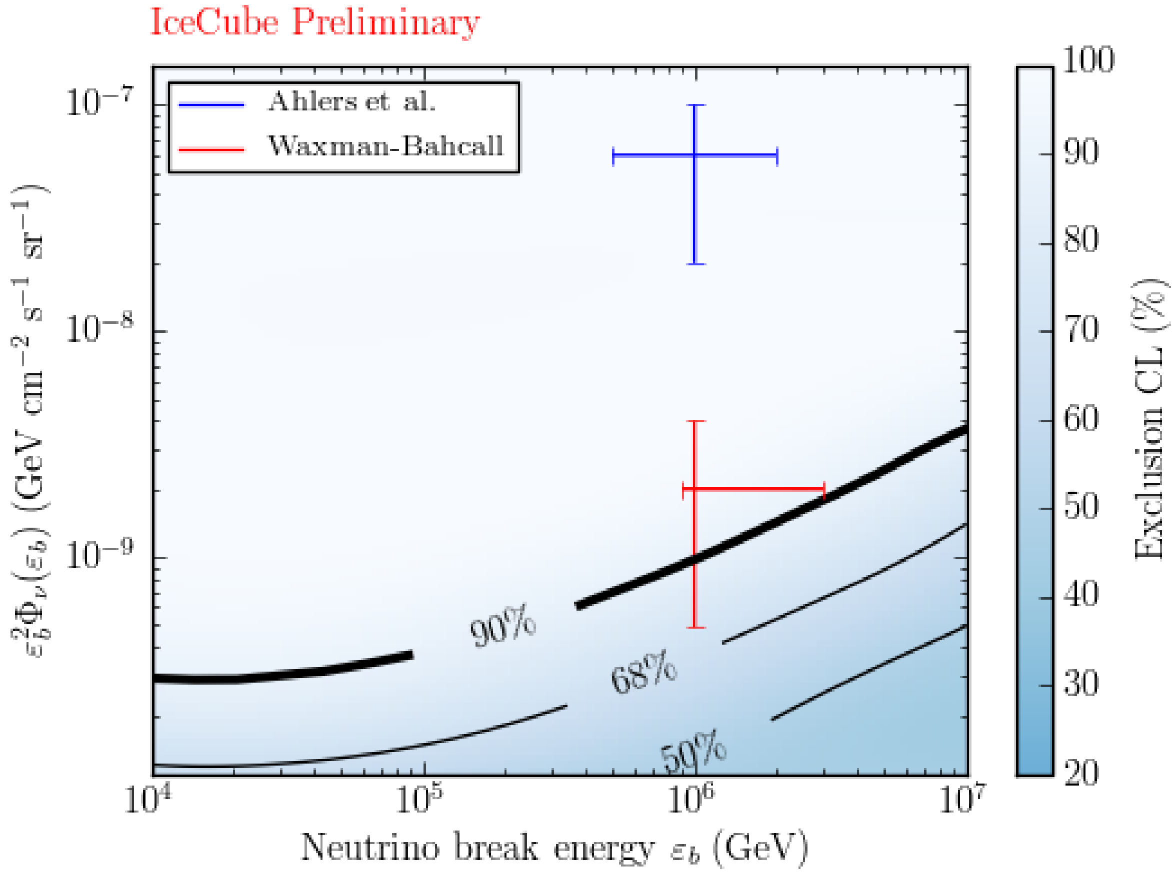

All sky search: post-trial p-value 23% no evidence for a neutrino source

# Neutrinos in coincidence with gamma-ray bursts?

- 4 years (IC40 + IC59 + IC79 + IC86-1)
- 506 GRBs
- No significant event observed

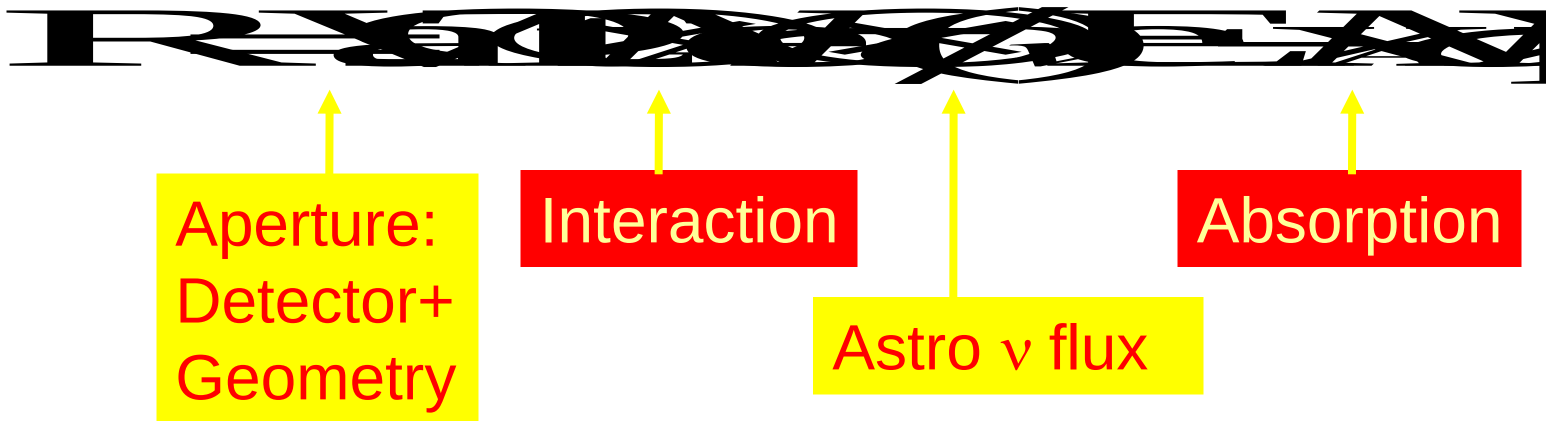
Upperlimit on a double broken power law type of GRB neutrino fluxes

$$\frac{dN}{dE} = \phi_\nu \begin{cases} E^{-1}{\varepsilon_b}^{-1} & E < \varepsilon_b \\ E^{-2} & \varepsilon_b < E < 10\varepsilon_b \\ E^{-4}{\varepsilon_b}^{2} & 10\varepsilon_b < E \end{cases}$$

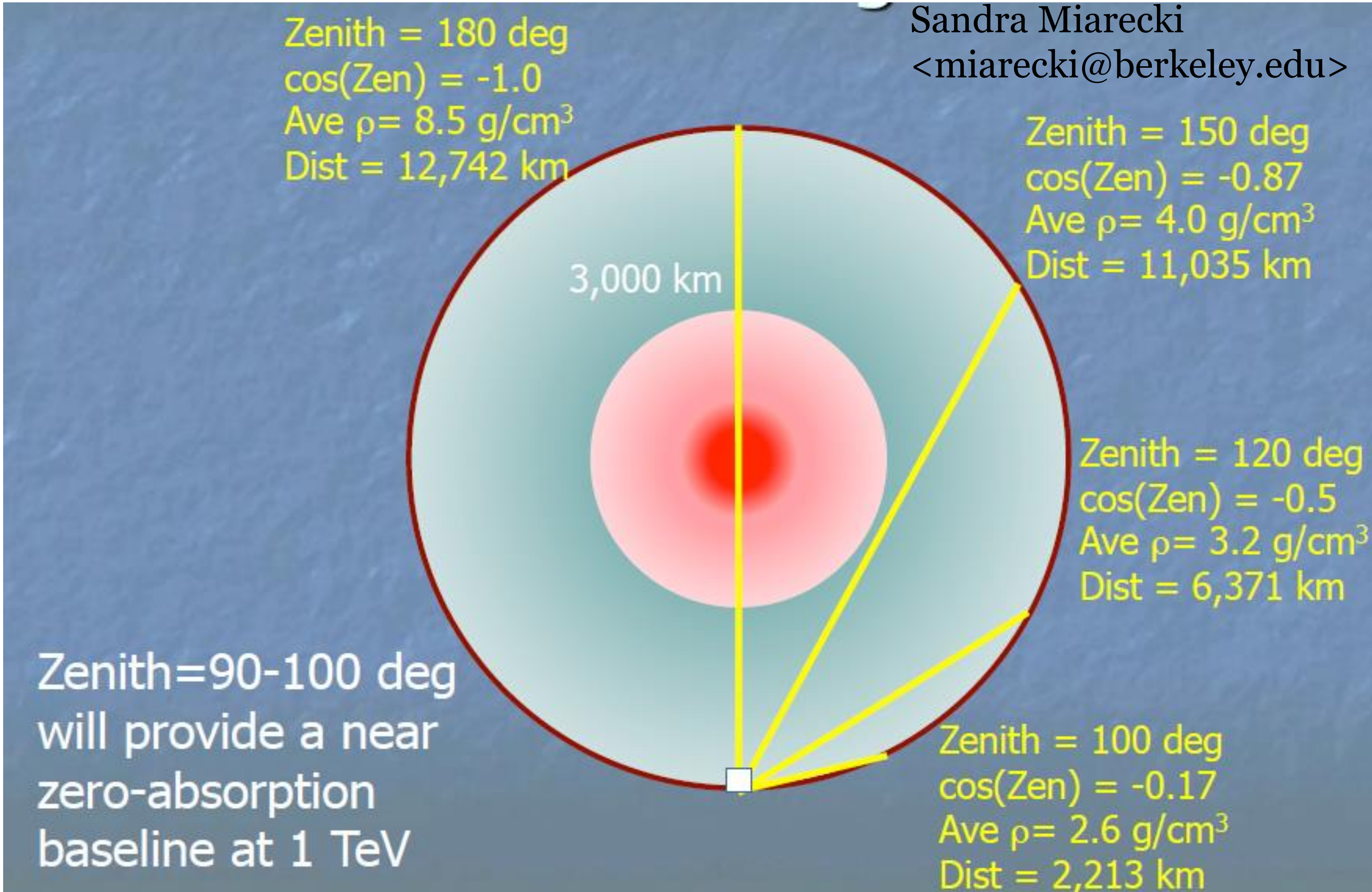



- Direction plus time (10-100s) cuts reduces background significantly
- Upperlimits are below the Waxman Bahcall model

# Implication to the neutrino-nucleus cross sections

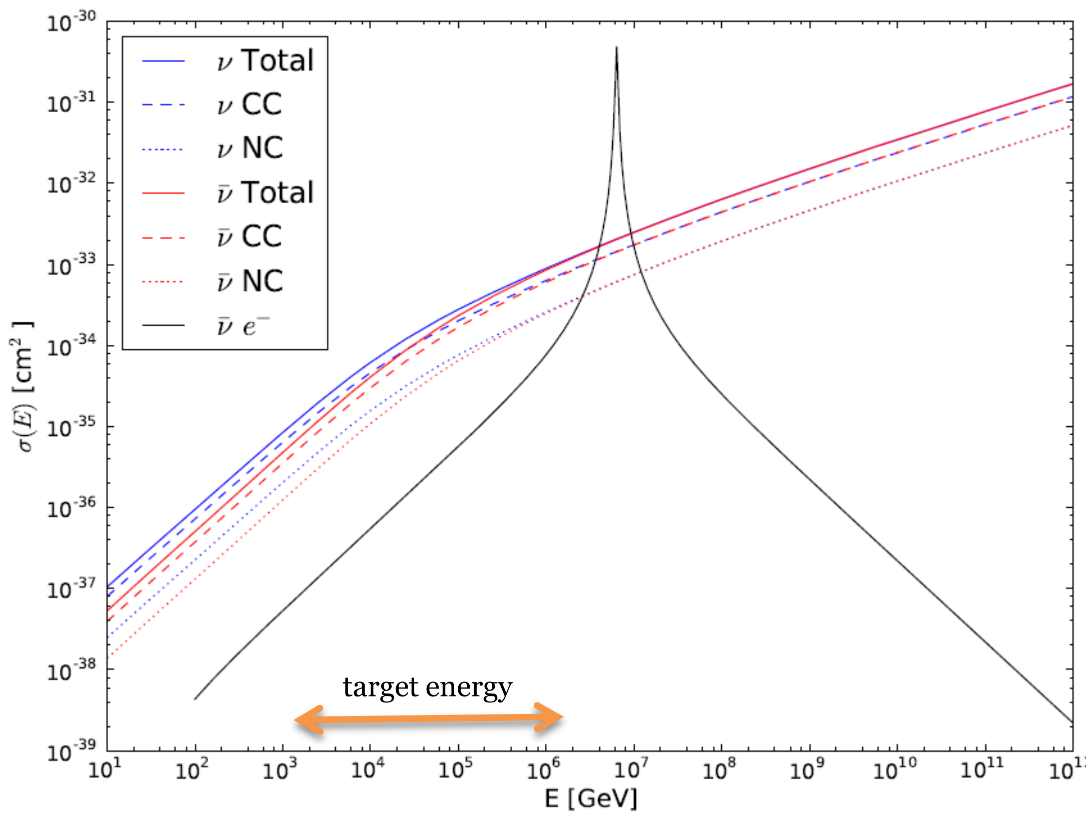


# Implication to the neutrino-nucleus cross sections



# Implication to the neutrino-nucleus cross sections

Reference model 'CSMS': A. Cooper-Sarkar, P. Mertsch, and S. Sarkar, JHEP p. 1108:42 (2011) using HERAPDF1.5




Raj Gandhi, Chris Quigg, Mary Hall Reno, and Ina Sarcevic. Phys. Rev. D, 58(9):093009 (1998)

Figure 3.3: Neutrino-nucleon and antineutrino-electron scattering cross-sections as a function of neutrino energy from [67] based on data from [64]. From bottom to top at low energy, the cross-sections are for $\bar{\nu}$ NC, $\nu$ NC, $\bar{\nu}$ CC, $\bar{\nu}$ total, $\nu$ CC, and $\nu$ total. The resonance peaked at 6.3 PeV is the antineutrino-electron resonance.

# What's beyond IceCube?

IceCube found:

- Working well at South Pole
- High level of astrophysical neutrino flux
  - ✓ cosmic ray sources are efficient neutrino sources
- Neutrinos above 1 PeV from Southern sky (3events/3years)
- Spectral indices and shape, $\phi \propto E^{-2.3}$ at high energies

We need more:

- Discoveries
  - neutrino point sources, PeV tau neutrinos, $\bar{\nu}_e e^- \rightarrow W^-$ Glashow resonance events, GZK neutrinos (E>10PeV)
- Precision measurements
  - cosmic neutrino spectra, flavors, anisotropy
- Particle physics
- And more…

# the Next Generation IceCube:

# IceCube-Gen2


***High Energy extension***

Scale: 100 strings, 10,000 PMT

volume 5 ~ 10 $km^3$, area 5 ~ 8 $km^2$

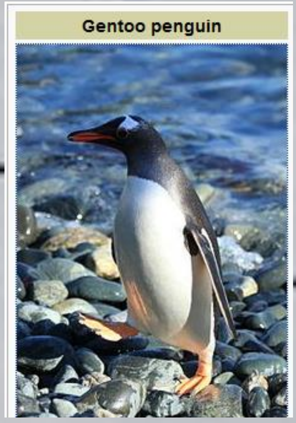
- optimal spacing under study

***Surface component a la IceTop***

A large surface extension for vetoing downgoing background

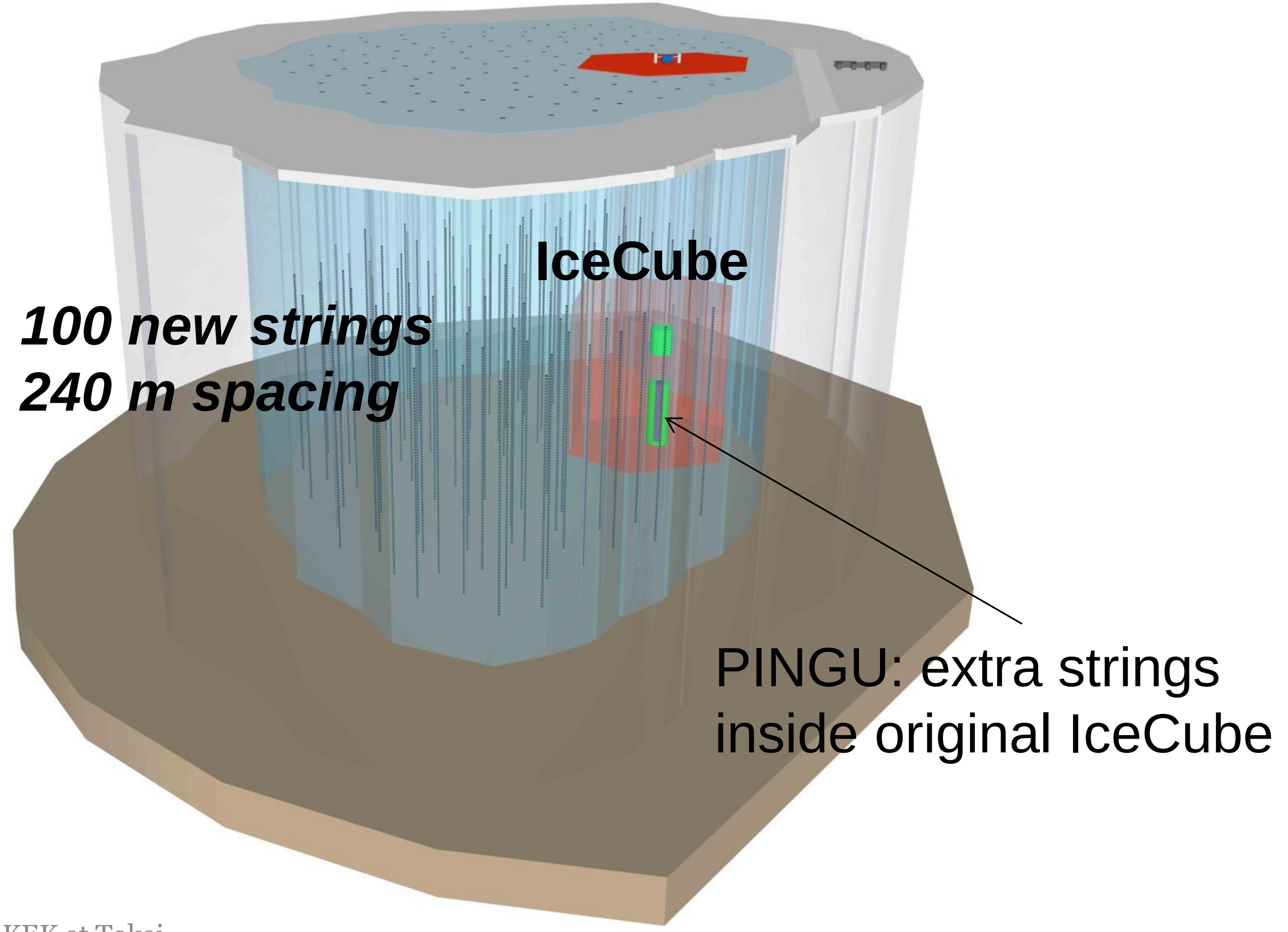
Up to 6 km from detector

- optimal size and density under study

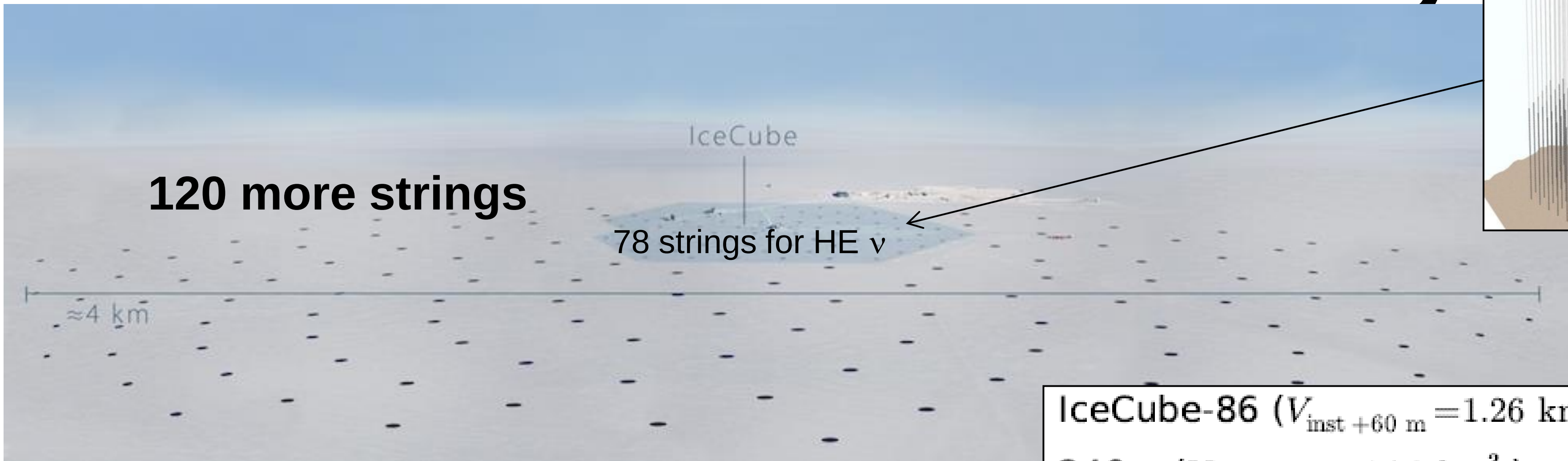


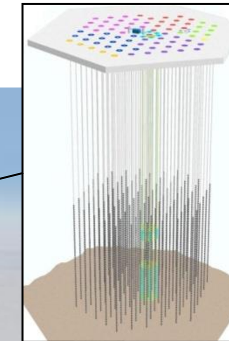
# A baseline configuration

- more statistics at high energy
- increase volume with more strings



# IceCube-Gen2 Geometry

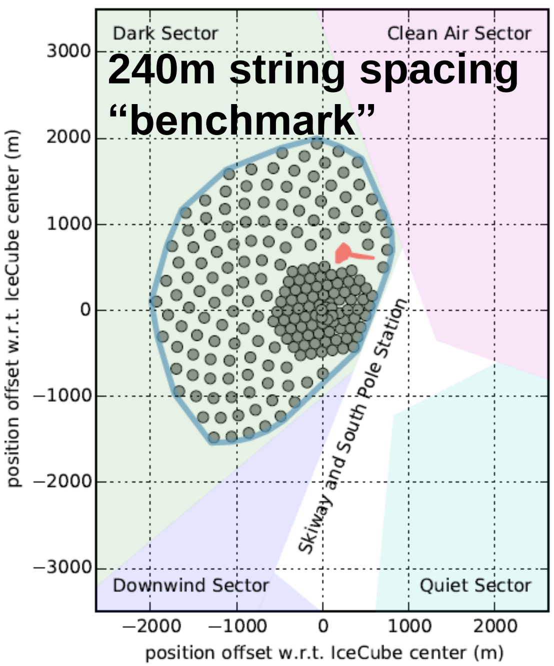


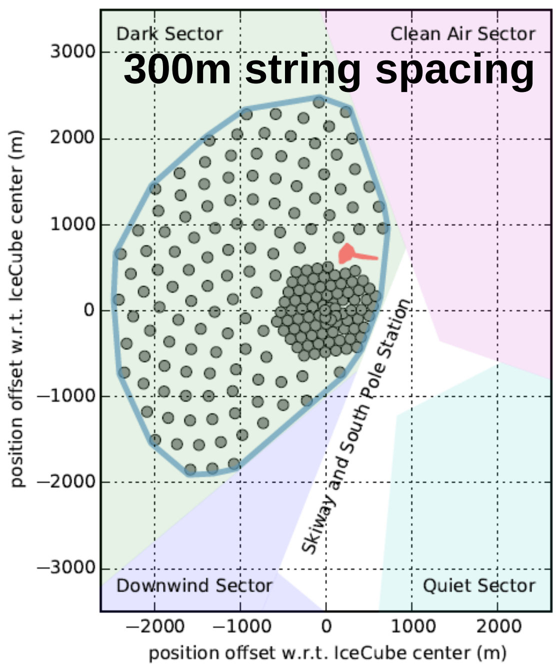



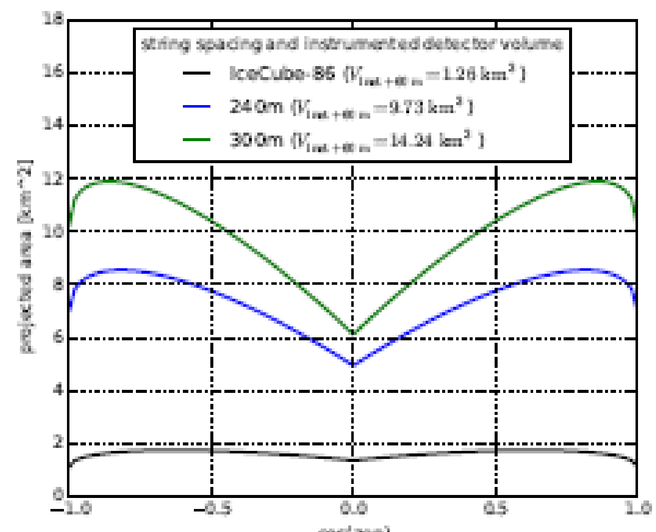
IceCube-86 ($V_{\mathrm{inst}+60\,\mathrm{m}} = 1.26\ \mathrm{km}^3$ )

240m ($V_{\mathrm{inst}+60\,\mathrm{m}} = 9.73\ \mathrm{km}^3$ )

300m ($V_{\mathrm{inst}+60\,\mathrm{m}} = 14.24\ \mathrm{km}^3$ )

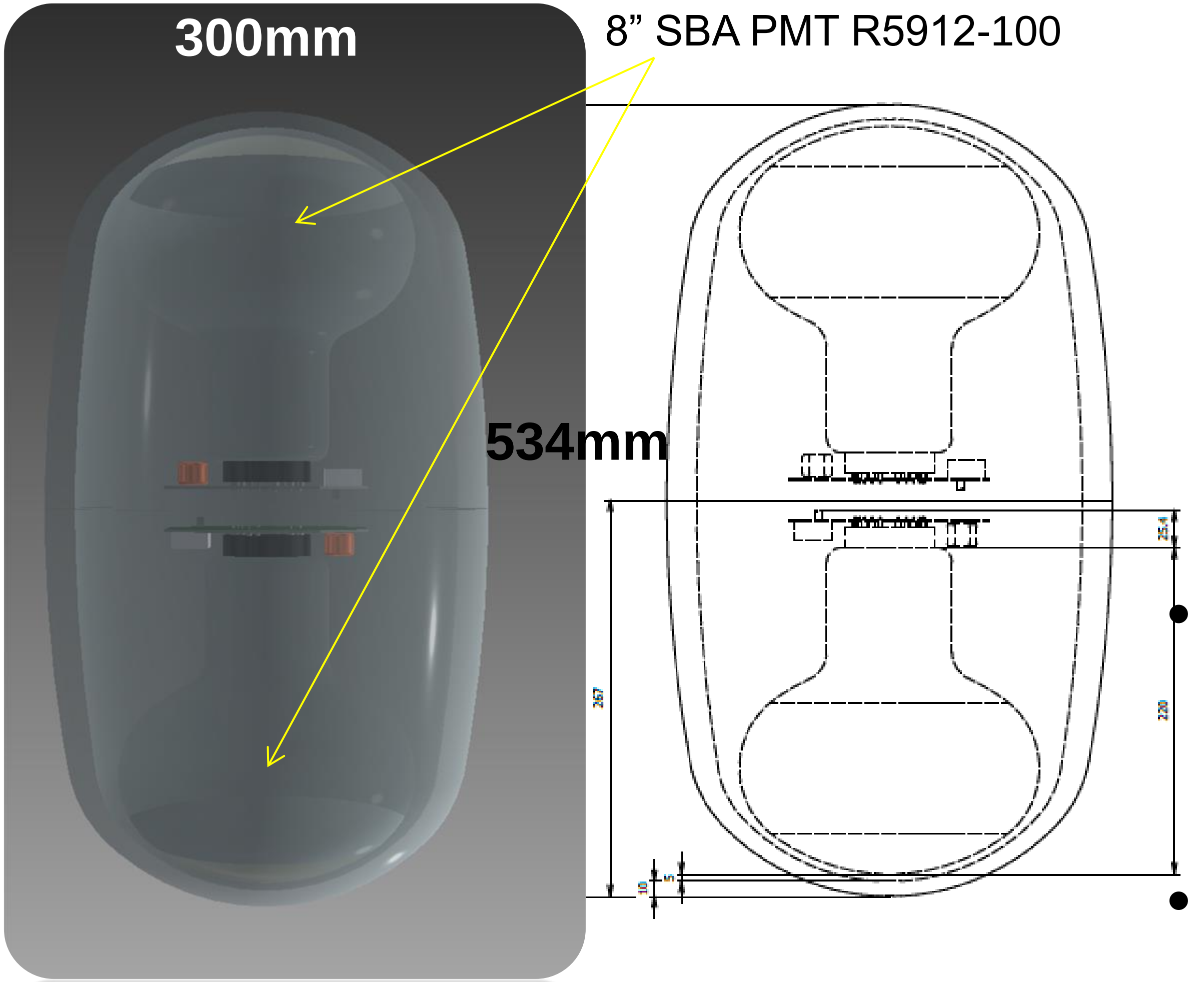



vertical horizontal

# New Optical Modules design proposal from Chiba for IceCube-Gen2: “D-EGG”



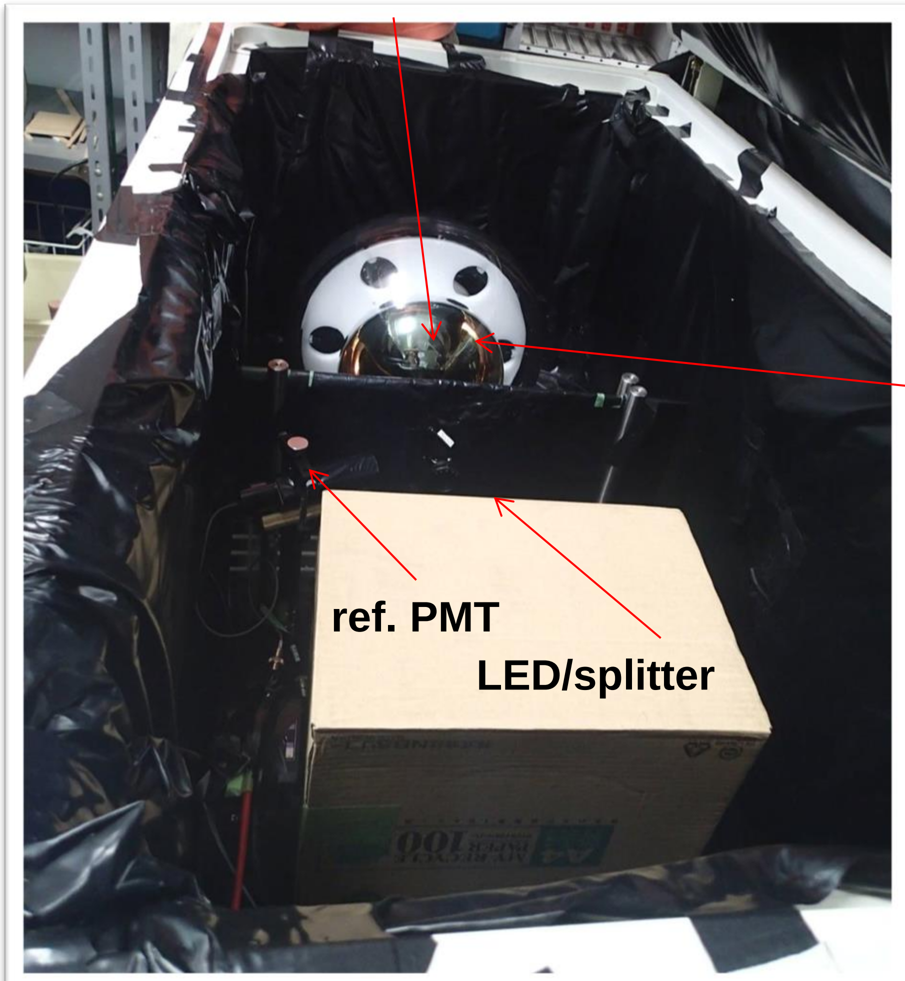

**to observe**

- **More signal events**
- **Better angular resolution**
- **Better muon veto**

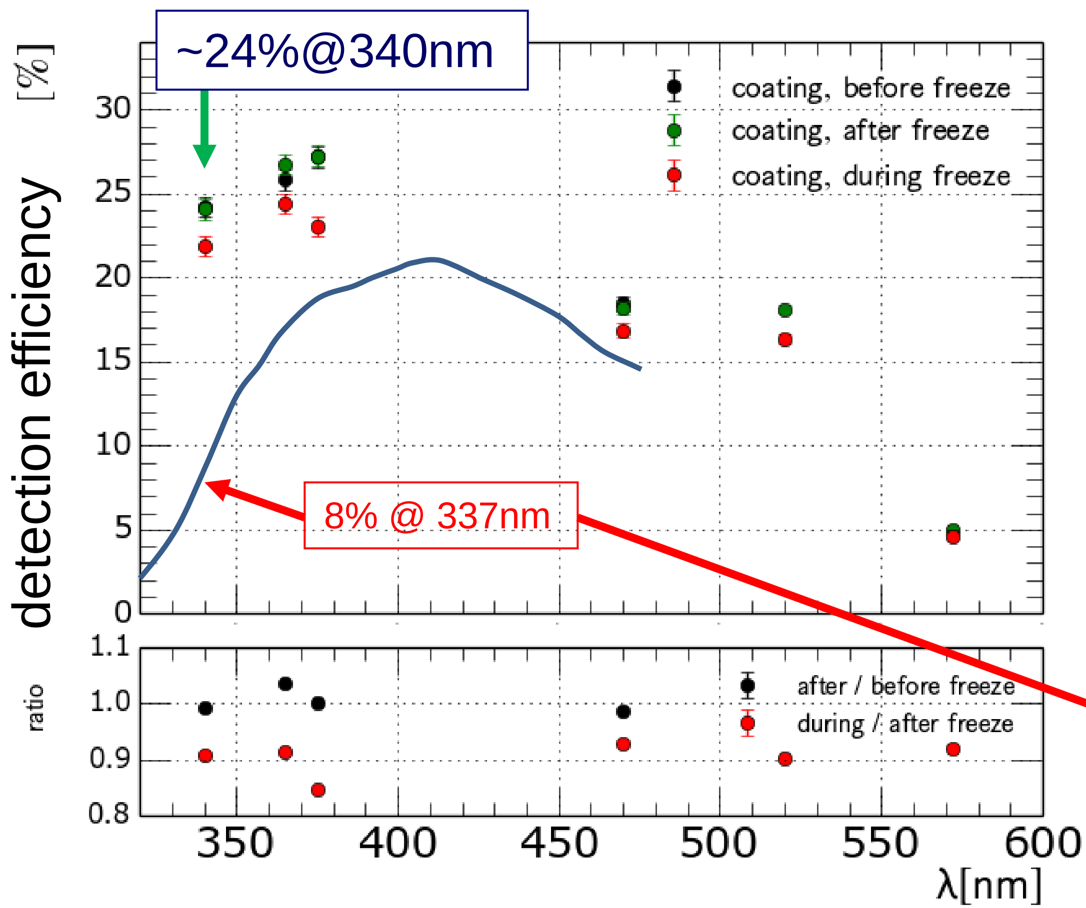
- Realize higher photon detection efficiency
- Up/down symmetric PMT configuration

# PMT + Glass measurement

Glass + PMT



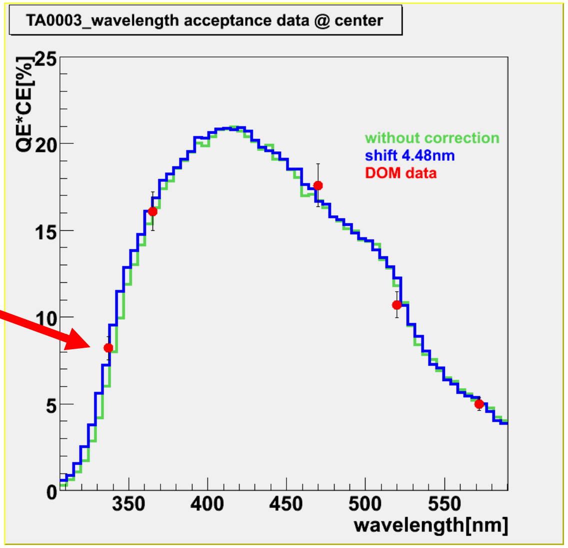

# PMT + Glass photon detection efficiency




detection eff. @ 340nm

bare PMT 27%
PMT + glass 24 %

The present IceCube DOM



# Summary

- IceCube has been fully operational since 2011, accumulated 3-full year samples + 4 years of partial operation data (22, 40, 59, and 79 strings
- Observed extraterrestrial diffuse neutrinos from different analysis methods as an excess from background only hypothesis
  - more than 3σ with muon neutrino upgoing track channel and more than 5σ level achieved with the starting event search with muon veto technique
- No indication of transient/continuous point sources yet

- High energy extension of the IceCube proposed – 5 times or more signal events to study the nature of neutrino fluxes and detect point sources. Improvements on the hardwares.
- Stay tuned!